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VHF OMNIDIRECTIONAL RADIO RANGE (VOR)

ELECTROMAGNETIC SPECTRUM MEASUREMENTS

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SYSTEMS RESEARCH AND DEVELOPMENT SERVICE

SPECTRUM MANGEMENT STAFF

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16. Abstract

This report presents VOR electromagnetic spectrum measurement techniques applicable to site survey, installation, maintenance, and interference alleviation activities. Spectrum displays of the VOR emission contain valuable system performance information. These displays contain significant detail which can be used for analyzing the performance of various parts of the system. A basic set of VOR radiated spectrum displays taken at specific ground locations would be of value as a part of the basic facility records. Subsequent display samples could be taken remotely without disturbing the facility. Comparison of these with the site records would give insight into system performance and assist in the maintenance and flight inspection activities.

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VHF OMNI-DIRECTIONAL RADIO RANGE (VOR)
ELECTROMAGNETIC SPECTRUM MEASUREMENTS

9.1   Purpose. To present VOR electromagnetic spectrum measurement
           techniques applicable to site survey, installation, mainten-
           ance and interference alleviation activities.

9.2   Operational/electromagnetic description. The VOR signals provide
           azimuth information centered on the facility for aircraft navi-
           gation purposes. The authorized emission is 21A9 (21 kHz band-
           width, A9 modulation). Between 108.00 and 111.95 mHz, VOR
           frequencies are interspersed with ILS localizer frequencies.
           The 112.00 - 117.95 mHz band is used exclusively for VOR at
           50 kHz intervals. See references No. 1 and 2 for VOR and
           DME/TACAN channelization and pairing. Reference No. 3 contains
           geographical spacing of frequency assignments required to avoid
           intra-system interference.   There are approximately 950 VOR
           stations in the U.S.A. This includes 910 conventional (four
           antennas) stations and 40 Doppler VOR (DVOR) stations (51
           antennas).

9.2.1   Conventional VOR. Most of the conventional VOR facilities are
           of the type shown in Figure 9-1 with the antennas mounted above
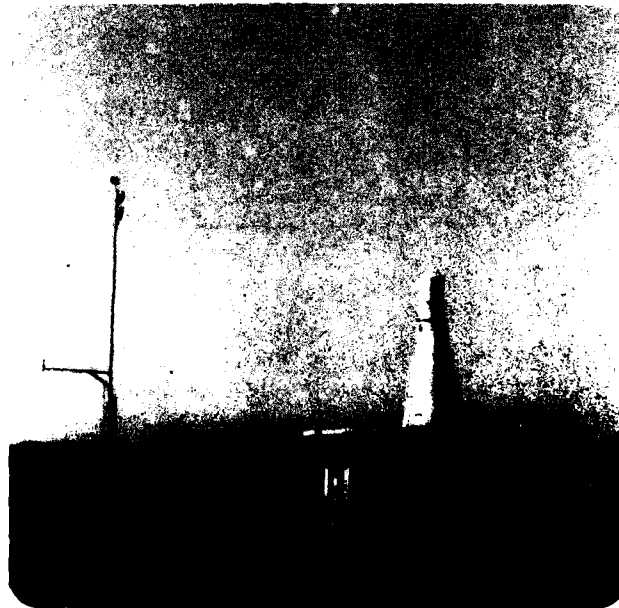

Figure 9-1. Conventional VOR facility. The four Alford
Loop antennas are housed in the conical section. The DME
or TACAN antenna is contained in the cylindrical top sect-
ion. The monitor pole is to the left.

a counterpoise about 12 feet above the ground on top of the
equipment room. Approximately 15% of the installations employ
the "mountain top" configuration where the antenna housing is
placed directly on a leveled off hill-top with no additional
counterpoise as shown in Figure 9-2. The transmitter building
is usually located beyond the "brow" of the hill below the
ground plane coupled to the antennas through some 300 feet of
low loss coaxial cable.

Figure 9-2. Mountain top VOR. The conical housing contains
four Alford Loop antennas and the top cylinder the TACAN
antenna. The monitor antenna is in the right background.

The electronics and resulting radiated spectrums of these two
VOR types are similar. A 200 watt transmitter radiates emissions
modulated 30% by both reference and variable 30 Hz azimuth infor-
mation, 28% by voice, and 6% by 1020 Hz identification. The 30 Hz
reference FM modulates a 9960 Hz (10 kHz abbreviation) subcarrier
which amplitude modulates the carrier by 30% as shown in Figure 9-3
center. This subcarrier is derived from a tone wheel containing
332 magnetic teeth which rotates 30 rps past a magnetic pickup
to develop (30 rps x 332 teeth) 9960 Hz. The variation in spacing
between the teeth causes the rate at which the frequency is
developed to vary (deviate) $\pm$ 480 Hz about the 9960 Hz average.
This is characteristic of an FM modulation index of 16 (30 Hz x 16 =
480). The resultant emission bandwidth (2 x 480) is seen in

10 dB/div

+ 10 kHz S.B.

10 Hz BW, 200 Hz/div, 10 sec/div

10 Hz BW, 200 Hz/div, 10 sec/div

Hz BW, 200 Hz/div, sec/div

10 dB/div

Mountain Top VOR 3/18/77

−10 dBm
30 dB input

+ 10 kHz S.B.

Carrier

kHz BW, 20 kHz/div, sec/div
AM Conventional VOR 3/21/77

−20 dBm
20 dB input

1 kHz BW, 20 kHz/div, 5 sec/div
FRR Conventional VOR 3/18/77

−20 dBm
20 dB input
atten

1 kHz BW, 20 kHz/div, sec/div

10 dB/div

30 Hz S.B.

60 Hz

Carrier

10 Hz BW, 20 Hz/div, sec/div

10 Hz BW, 20 Hz/div, 10 sec/div

10 Hz BW, 20 Hz/div, sec/div

Figure. Spectrum comparison of three VOR facilities in the area. Note the oscillating amplitude roll-off of the harmonics in the upper facility which is accentuated on the middle facility. It is visible in the smoothed decay envelope of the lower facility. The unbalance between the ± 10 kHz subcarriers also appears in the ± 30 Hz sidebands of the upper facility. The variable pattern size is easily seen (10 Hz/div) in the ripple in the left hand display.

Figure 9-3 right. The bessel amplitude of the carrier and
sideband lines is shown in Figure 9-8. The reference carrier
and ± 10 kHz subcarrier are fed in phase to all antennas to
produce the circular pattern shown in Figure 9-4. The 30
Hz detected signal in the aircraft receiver will be a similar
amplitude and phase at a particular distance and altitude on
any azimuth around the facility from this reference emission. The
30 Hz variable signal is developed by the rotating sideband pattern

Figure 9-4 VOR Signal Generation Concept
As the pattern rotates clockwise the detected variable signal
in the aircraft receiver lags the reference signal one degree
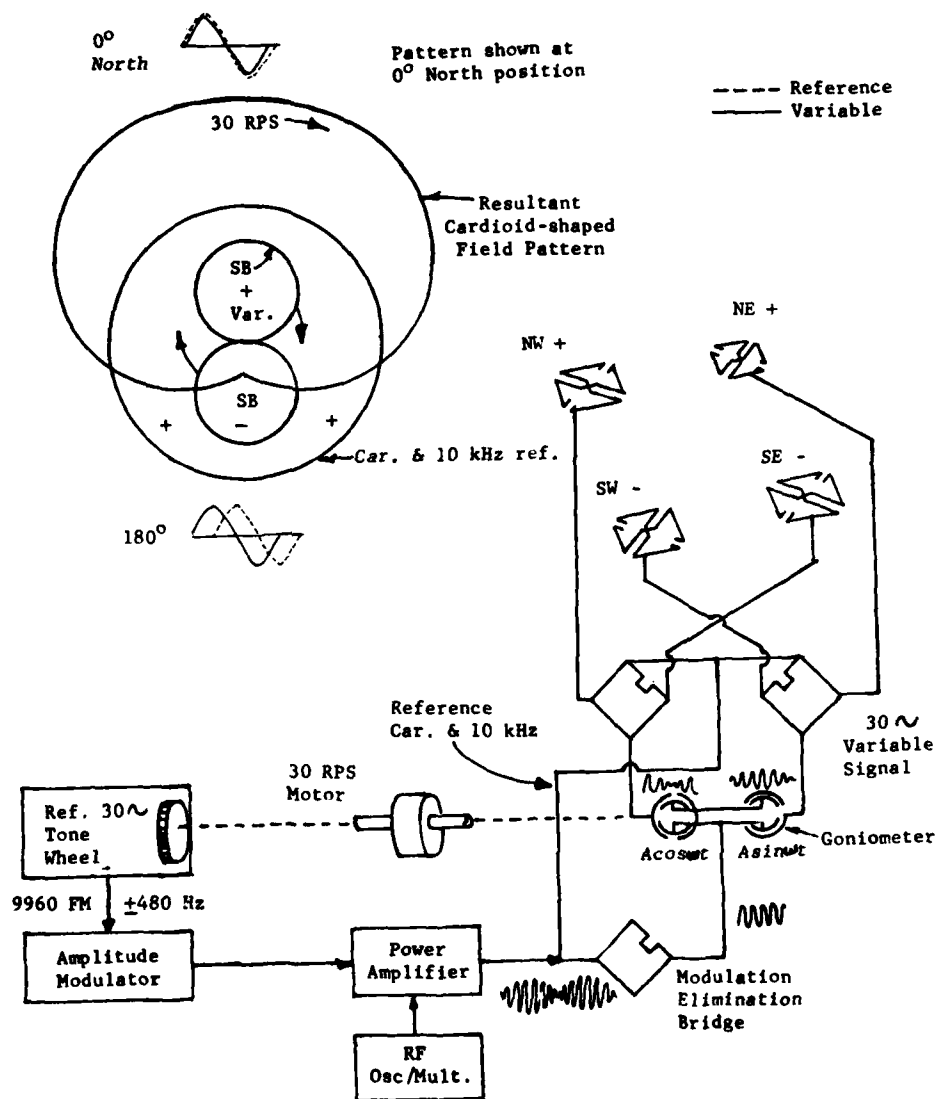in phase for each degree of azimuth traversed around the site.

as it space-amplitude modulates the carrier by 30% as shown
in Figure 9-4 to produce the Figure 9-3 left and 9-6 spectrums.
The essential functions for generating these antenna patterns
are depicted in Figure 9-4. The relationship between the 30 Hz
variable and reference signal timing is preserved by mounting
the goniometer and tone wheel, respectively, on the same motor
shaft. The RF phase relationship in the variable and reference
signals is preserved by separating them after the power amplifier.
The amplitude modulation is removed to present a constant amplitude
signal to the goniometer. The two outputs of the goniometer reach
their maximums 90° apart to produce sine and cosine inputs to
their respective antenna pairs (which are 180° out of phase with
each other). This combination creates a two lobe field pattern
rotating at 30 rps. The reference signal is applied to a phase-
shifting bridge to enable the carrier and 10 kHz subcarriers to
be coupled to the four antennas in phase to produce an omni-
directional pattern. The combination of this circular reference
and the twin-lobe variable patterns creates a cardioidshaped
resultant pattern rotating in space at a rate of 30 rps. The
amplitude variation produced in the receiver as this pattern
passes the aircraft can be seen as a ripple on the spectrum
envelope in the lower left Figure 9-3 display of carrier and
± 30 Hz sidebands. As the airplane flies clockwise around the
VOR, the detected variable signal in the receiver lags the
reference signal one degree in phase per degree of azimuth
traversed. It is noted that while the preponderance of VORs
presently installed are configured to operate as described above,
a new generation is being introduced which is solid-state and
achieves the equivalent signal without rotary parts. A 30 Hz
generator and phase shifter drive balanced modulators to produce
the variable signal antenna inputs previously generated by the
goniometer. The AFC utilized to maintain the RF phase relationship
between the carrier, 10 kHz subcarrier, and variable sideband
emissions may cause somewhat different spurious products at the
20, 30, 40, 50 kHz, etc. intervals than the conventional VOR.

9.2.2   <u>VOR Spectrum Measurements</u>. When making spectrum measurements the
        input levels to the instruments and I.F. gain adjustments must
        be within the linear range of operation in order not to contri-
        bute spurious components or distortion to the signal display.
        Tests were made on the analyzer used for the displays in this
        Chapter to determine linear conditions for a VOR type signal
        prior to making site measurements. Two generators were tuned 10
        kHz apart with 11 dB amplitude difference (typical of a DVOR) in
        the 108-118 MHz band to provide input to the analyzer. The
        analyzer input attenuator and I.F. gain controls were adjusted in
        combination for particular reference level calibration to deter-
        mine at what mixer input magnitude spurious signal components
        were self-generated by the instrument. While these spurious
        components were generally not objectionable for mixer inputs
        of -30 dBm, the input attenuator was adjusted to limit the mixer

input in most of the actual measurements to -40 dBm or less to provide a margin of safety. In the top-center display of Figure 9-3, for example, the top line reference level is given as -10 dBm. An input attenuator setting of 30 dB is used which limits the displayed carrier at -23 dBm to -53 dBm at the mixer. Additionally, the maximum signal component can only exceed the selected reference level by a few dB before self-generated display non-linearities appear. When expanding a low amplitude emission to obtain more detail the main carrier may be off the display; however, it is still present at the mixer and will affect the linearity of the small component displayed if a safe level is exceeded. When optimizing the input attenuator and I.F. gain controls to obtain adequate display amplitude and low noise this carrier amplitude must be considered. When instrumentation modes are changed, the display validity is checked by varying the input attenuator to see if all the components reflect corresponding changes in amplitude. Internally generated spurious components as a rule do not reflect these changes directly (linearly, proportionally). The label on each spectrum photo or chart recording should contain the reference level, input attenuator setting, instrument bandwidth (resolution), and scan rate (Hz/div, time/div) to enable interpretation of the display. If absolute as well as relative magnitudes are important the antenna type, orientation, line losses, and any other factors affecting amplitude of signal display must also be included. The instrumentation used to obtain the spectrum photographs in this VOR chapter is shown in Figure 9-5. A biconical (frequency broadbanded) antenna was used; however, the choice of an antenna type is not critical so long as the same orientation is maintained for all spectrum measurements where relative amplitude is important. A tuneable dipole is more directional where direction finding is important and is much less vulnerable to high wind damage (preferable when mobile operation is envolved). The biconical offers some advantage over dipole antenna when frequency changes within its band limits are made often over a wider range than the tuneable dipole covers without readjustment of element lengths.
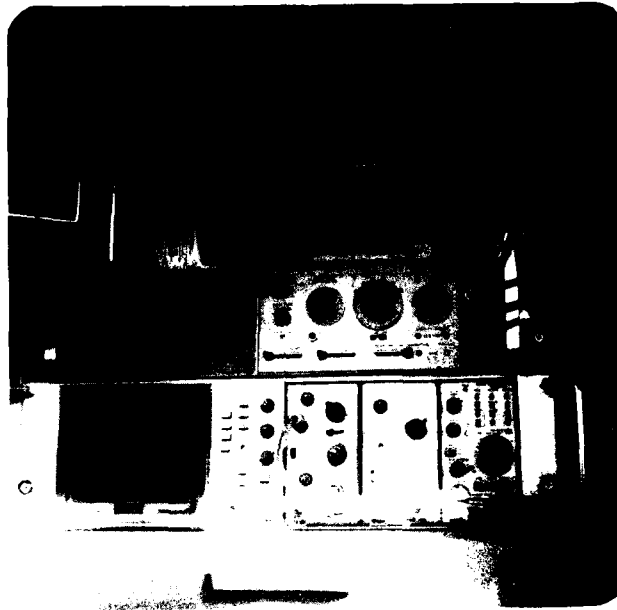
Figure 9-5 Spectrum Analyzer in the Spectrum Characteristics
Analysis and Measurement Vehicle (SCAM) shown producing a
linear display of the VOR 9960 Hz subcarrier. The equipments
shown include HP141T Display Section with HP8553B-H26
(modified to tune through 118 MHz) RF plug-in at right of
screen and HP8552B I.F. plug-in below it. The HP8445B Auto-
matic Preselector above the 141T and the Tektronix Storage
Oscilloscope Model 7622/R7633 with Dual Trace Amplifier Model
7A18/7A18N and Dual Time Base 7B53A/7B53AN below the 141T
were not used in this measurement. The HP197A Oscilloscope
Camera is swung to left of screen.

9.3   Analysis of Conventional VOR Spectrum. A random sampling of
       three VORs (including one "mountain top") in the vicinity
       produced the spectrum comparisons in Figure 9-3. Note the
       oscillation in ± 20, 30, 40 and 50 kHz harmonic roll-offs

in the upper and middle facility spectrums (center) while
the harmonics fall off in a more orderly manner on the lower
facility. This variation in emission spectrums is typical
of VORs operating in the 100 kHz channeling environment. Since
the amplitudes vary in the display as a function of analyzer
bandwidth there is international discussion on how the relative
amplitudes are to be determined (see discussion concerning
Figure 9-9 and in section 9.3.1 below). As the 50 kHz channeling
is implemented the ability of the higher order harmonics from one
facility to interfere (course errors) with the adjacent frequency
channel becomes of interest. The associated question of how
much these components need to be attenuated to make interfering
effects negligible needs to be considered integrally with the
question of how to measure them in order to enable a satisfactory
information exchange between the engineers concerned with both
problems. Note the unbalance in 10 kHz subcarrier levels in
the top-center display. This may indicate a need to neutralize the
transmitter. This unbalance also appears in the top-left 30
Hz sidebands which are developed from the composite addition of
the reference and variable patterns. While these are primarily
frequency domain displays, an amplitude versus time (time domain)
effect is seen as 30 Hz ripple on the main display envelope of
the bottom left display. The cardioid pattern passing the
analyzer antenna at 30 rps causes this amplitude fluctuation
to produce 15 peaks per division as the trace scans at 0.5 sec/div
(15 peaks/div $\div$ .5 sec/div = 30 peaks/sec).

9.3.1   **Modulation % Measurements with Spectrum Analyzer.** In the 300 Hz
BW upper left display of Figure 9-6 the carrier is augmented by
the 30 Hz variable sidebands   contributing energy within the
bandpass of the analyzer. This -23 dBm level drops about 2.3 dB
to -25.7 dBm in the center-left photo as the narrowed bandwidth
(10 Hz) removes the 30 Hz sidebands from the carrier envelope.
While overall amplitudes vary over a period of time from power
fluctuation, antenna orientation/propagation effects, etc. the
correction factor 2.28 dB should be subtracted from VOR carrier
amplitudes when the analyzer bandwidth is not narrow enough to
separate the sidebands from the envelope if relative amplitudes
of components within the display are being interpreted. This
2.28 correction for DSB modulation is calculated as follows:

E_s $\diagdown\!\!\!\diagup$ $E_s = .15$

$E_c = 1$
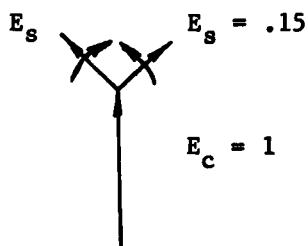
$$m = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} = .3 \quad \text{For 30\% modulation}$$

$$m = 2E_s/E_c \times 100\%$$

Where: E_c = carrier
E_s = sideband

Note 60, 90, 120, 150 Hz harm.

-20 dBm ref.
20 dB atten

113.5 MHz Carrier

+ 10 kHz

10 dB/div

10 dB/div

300 Hz BW, 20 kHz/div, 10 sec/div

10 Hz BW, 100 Hz/div, 10 sec/div

120 Hz lines out to ± 1 kHz

Car. ± 30 Hz SB, ± 60,90,120,& 150 Hz harm

Carrier

30 Hz S.B.

10 Hz BW, 500 Hz/div, 10 sec/div

10 Hz BW, 50 Hz/div, 10 sec/div

Note lines at 120 Hz intervals.

Carrier and ± 30 Hz S.B.; ± 60, 90 Hz harm

10 Hz BW, 200 Hz/div, 10 sec/div

10 Hz BW, 20 Hz/div, 10 sec/div

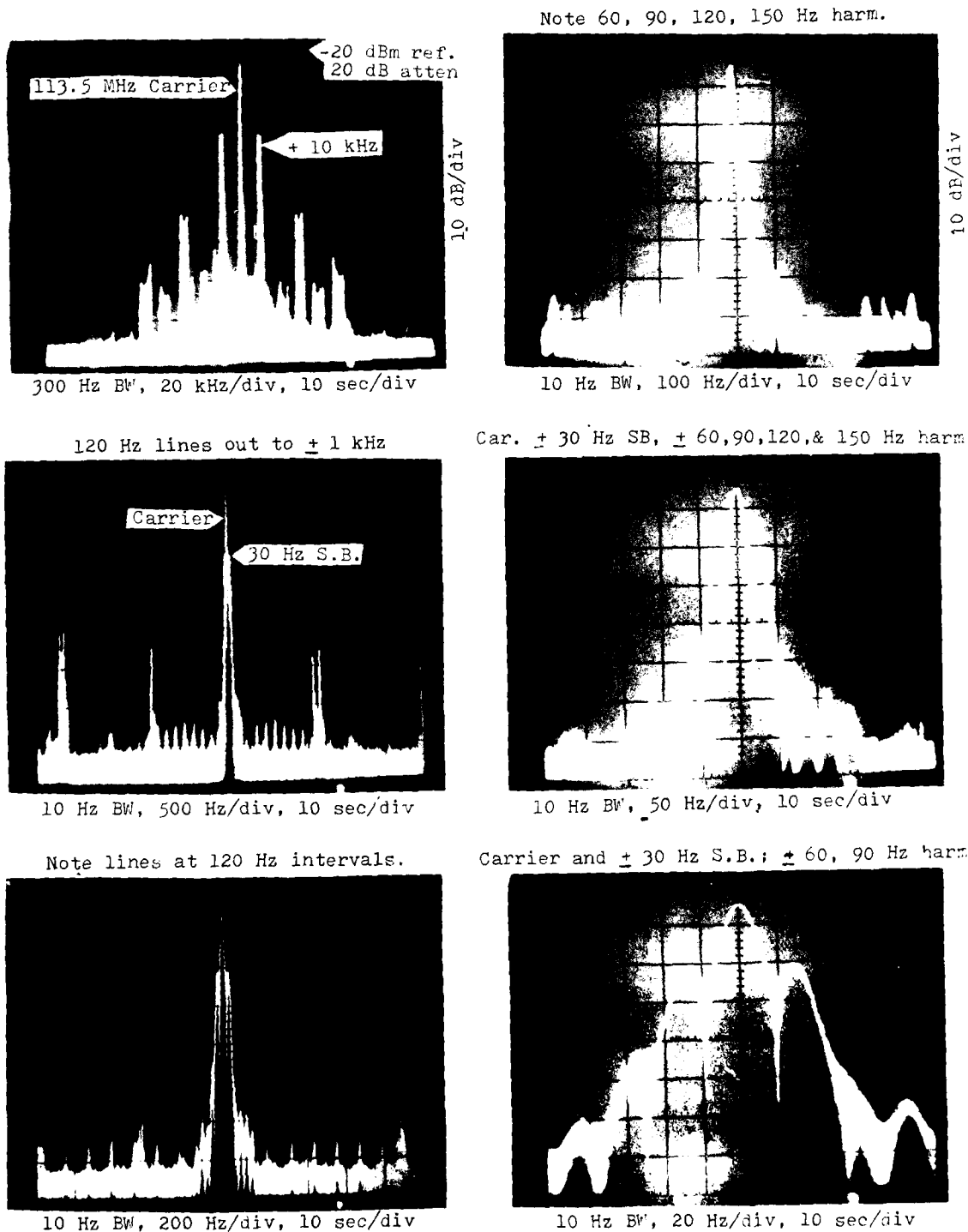Figure 9-6 Conventional VOR spectrum with reference and variable sideband levels emphasized. The upper-left shows the ± 10 kHz subcarriers at -42 dBm (see Figure 9-9 for correction to -41.5 dBm.). See section 9.3.1 for decrease in carrier level with analyzer bandwidth, and carrier to sideband level differences. See section section 9.3.2 for 30 Hz harmonics. See 9.3.4 for analyzer drift effects.

For double sideband: $E_{max} = (E_c + 2E_s)$

$$E_{min} = (E_c - 2E_s)$$

Substituting and rearranging we get $E_s = 0.15$ where the carrier $E_c = 1$. The difference between the peak amplitude appearing on the screen with the 30 Hz sidebands contained in the carrier envelope ($E_c + 2E_s = 1.3$) and the carrier seen without sidebands ($E_c = 1$) when the analyzer resolution bandwidth is reduced to 10 Hz is:

$$\Delta E^+ \text{ (dB)} = 20 \log E_{max}/E_c = 20 \log 1.3/1 = 2.28 \text{ dB}$$

The instantaneous lowering of the carrier due to the sideband vector cancellation within the bandpass envelope is in the order of:

$$\Delta E^- \text{ (dB)} = 20 \log E_c/E_{min} = 20 \log 1/.7 = 3.1 \text{ dB}$$

The peak to peak ripple (E_{pp}) to be anticipated on the bandpass envelope enclosing the carrier and 30 Hz sidebands is then:

$$E_{pp} \text{ (dB)} = 20 \log E_{max}/E_{min} = 20 \log 1.3/.7 = 5.377 \text{ dB}$$

This variation brightens the trace over this vertical range in displays when the analyzer controls are set to distinguish it. This variation can appear to be more or less when imposed on non-linear mechanisms in the emission and display process.

The carrier plus sideband envelope amplitude then can vary as much as E_{pp} (5.377 dB) if the antenna array is assumed to be omnidirectional so that the variation in pattern amplitude is due primarily to the sideband RF feed from the goniometer. Inspection of the lower left photo in Figure 9-3 indicates that this pattern fluctuation approaches zero near the carrier frequency as seen with a 10 Hz bandpass (discussed in section 9.3.8).
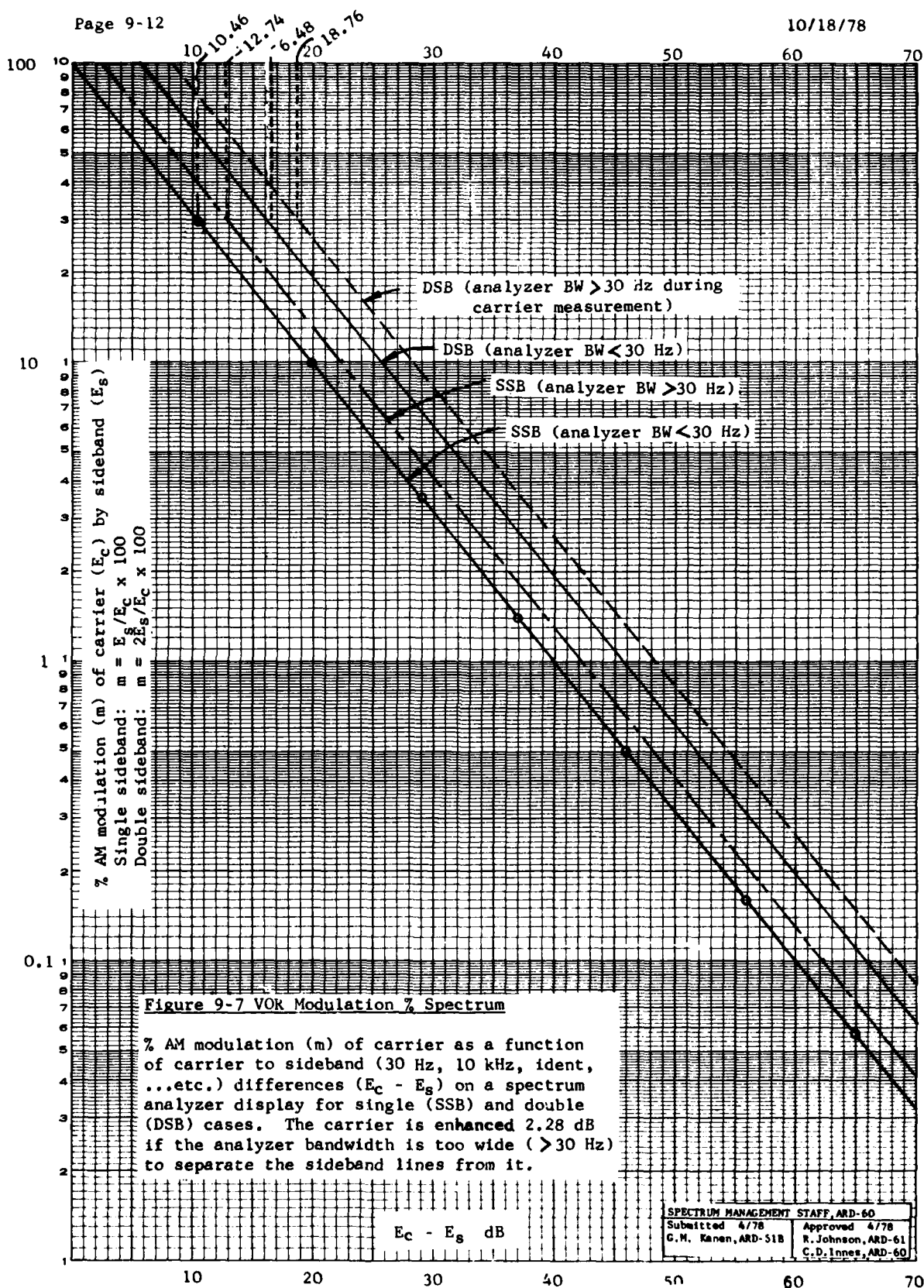
This antenna pattern ripple (as much as 6 or 8 dB) is seen in
Figure 9-9 (lower left display). Whether the maximum envelope
magnitude (incorporating the 2.28 dB correction) is recorded
depends on whether the pattern lobe passes the measurement
location during the time interval that the carrier is within
the sweeping analyzer bandpass. To ensure a good recording
of the maximum amplitude, several pattern rotations should
occur while the bandpass is in the carrier vicinity. For
example, if it is desired to measure the percentage of modulation
the 10 kHz sideband offers the carrier, an arbitrary 5 kHz/division
dispersion and 1 kHz bandpass would put the carrier under the
analyzer bandpass for 1/5 division. A 1 sec/div sweep rate would
then keep the carrier in the bandpass for 1/5 second to expose
the screen to 30/5 = 6 rotations of the pattern. If the sweep
rate is increased to 0.1 sec/div the bandpass would only encounter
0.6 rotation of the ripple cycle and might record the minimum
instead of the maximum (or something in between). This problem
is illustrated with other control settings in the lower left
(10 kHz BW, 20 kHz, 0.2 sec/div) display of Figure 9-9. One
antenna maximum occurred as the scan passed the carrier frequency
and the peak-to-peak somewhat exceeds the 5.4 dB calculated in this
section (although interpretation of this in this photo is compli-
cated by the rapid fall-off of the bandpass characteristic). If
the scan rate were changed to 0.1 sec/div the ripples recorded
per division would be halved and an antenna pattern maximum might
not have been displayed. This likelihood increases as the band-
width is narrowed, the sweep time is reduced, and the dispersion
(freq/div) is increased.

The difference in carrier and sideband magnitudes for both the
30 Hz and 10 kHz subcarrier cases is of interest for display
interpretation. For 30% modulation (double sideband) this is:

$$E_c - E_s \text{ (dB)} = 20 \log E_c/E_s = 20 \log 1/.15 = 16.478 \text{ dB}$$

however, the displayed difference with a 1 kHz bandpass (wide
enough to faithfully report the 10 kHz amplitude) will be
16.478 + 2.28 = 18.758 dB because of the presence of the 30
Hz sidebands in the carrier envelope. See the close agreement
in the 1 kHz BW displays of Figures 9-3, 9-9.

To measure the amplitude difference between the carrier and the
30 Hz sidebands the analyzer bandwidth must be narrowed to 10 Hz
(or something appreciably less than 30 Hz) to separate these
components so the 2.28 dB error will not be present in the carrier
magnitude.

Figure 9-7 VOR Modulation % Spectrum

% AM modulation (m) of carrier as a function
of carrier to sideband (30 Hz, 10 kHz, ident,
...etc.) differences ($E_c - E_s$) on a spectrum
analyzer display for single (SSB) and double
(DSB) cases. The carrier is enhanced 2.28 dB
if the analyzer bandwidth is too wide ($>$30 Hz)
to separate the sideband lines from it.

SPECTRUM MANAGEMENT STAFF, ARD-60	
Submitted 4/78	Approved 4/78
G.M. Kanen, ARD-51B	R. Johnson, ARD-61
	C.D. Innes, ARD-60

For single sideband as in the single sideband doppler (DVOR)
E_s relative to E_c is determined as follows:

$$E_s = .3 \qquad m = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} = .3 \qquad \text{for 30\% modulation}$$

$$E_c = 1 \qquad \text{Where:} \quad E_{max} = E_c + E_s, \; E_{min} = E_c - E_s$$

$$\text{Substituting we get:} \quad E_s = mE_c = .3$$

The $E_c - E_s$ (dB) $= 20 \log E_c/E_s = 20 \log 1/.3 = 10.458$ dB

This 10.458 carrier to sideband difference will be displayed as
(10.458 + 2.28) 12.738 for analyzer bandwidths too wide to
separate the 30 Hz sidebands (such as the 1 kHz BW required to
report the 10 kHz amplitude without correction). As in the double
sideband case no correction for carrier amplitude will be necessary
when the analyzer bandwidth has been narrowed sufficiently to
separate the 30 Hz sidebands for modulation level comparison.

See Figure 9-7 for carrier and carrier plus sideband to sideband
amplitude differences in the analyzer display as a function of
modulation percentage for both the double and single sideband
cases.

9.3.2   Presence of 30 Hz harmonics in display. The presence of 120 Hz
lines is evident in the middle and lower displays in Figure 9-6
as well as the upper left. These are seen to originate near the
carrier and increase out to about 600 Hz $\pm$ from the carrier and
then decrease to disappear in the noise at about 1100 Hz. This
type of display may prove useful to assist course error reduction
efforts. See IMP 6790.4 Installation and Maintenance Handbooks
(reference 4 and 5) for discussion of how 30, 60, and 120 Hz
components produce duantal (1 positive and 1 negative excursion),
quadrantal (4), and octantal (8) course errors, respectively.
In general, if the 120 Hz components similar to those shown in
the displays are sufficiently strong it may be expected to find
octantal error on the facility. In the right hand displays 60,
90, 120, and 150 Hz products are evident. The 120 Hz is seen
to be larger than the 90 or 150 Hz products and in the upper
right multiples of 120 Hz decrease to a low at 240 Hz to begin
the series discussed above for the middle-left display.

9.3.3   **Voice and identification tones in spectrum.** Voice emissions
        appear in the middle left display of Figure 9-6 at -2.2, 1.2, and
        2.5 kHz, separated by 60 and 30 seconds scan time, respectively.
        The voice may show anywhere within the approximately $\pm$ 3 kHz
        emission bandwidth if the timing of the scan coincides with the
        voice transmission interval; whereas, the tone appears at the
        1020 Hz locations when these are being traversed during identi-
        fication intervals. In addition these audio voice and tone
        signals intermix and appear in the higher order harmonic emissions
        $\pm$ 20 or 40 kHz, for example, as shown in Figure 9-12 and 9-13
        with augmenting discussion in section 9.3.1.

9.3.4   **Spectrum analyzer (or other instrument) drift effects on displays.**
        When the bandwidth and scan/division of the spectrum analyzer
        have been reduced to bring out details of components over a small
        frequency range it is necessary to increase the scan time in
        order to remain in calibration. At these greater scan time/division
        writing rates any appreciable drift of the analyzer oscillator
        causes a non-linear frequency display such as appears in the
        Figure 9-6 lower right-hand photo. To compensate for a display
        drift to the left, the carrier was manually tuned to the right
        of center so that by the time the single-sweep scan was initiated
        and had time to sweep 5 divisions at 10 seconds/division (50
        seconds) the carrier had drifted to center the display. In the
        process the -30 Hz sideband was traced before it had time to drift
        the amount needed so it appears at -28 Hz (2 Hz high), and in turn,
        the upper +30 Hz sideband has had too much time and has drifted
        down to +28 Hz (2 Hz low) relative to the carrier. This non-linear
        frequency error occurs whether the signal is initially offset to
        compensate for the drift or not. When both the analyzer and
        signal are drifting a stable generator marker can be injected
        to assist analysis. In general, if the marker display is drifting
        but maintains a fixed offset from the signal the analyzer is at
        fault; whereas, if the marker display remains fixed on the screen
        and the signal is drifting the analyzer is stable. When both the
        analyzer and the signal being measured are drifting the operator
        must stay loose and work fast with the offset principle in order
        to obtain a centered display and not lose the signal in the process.
        A considerable loss in time occurs when the operator runs out of
        "fine tuning" range and has to broaden the frequency scan, band-
        width, disable the stabilizer, reset the "fine tuning" to center
        of range, re-tune the "coarse tuning" in order to find the signal
        and start the "gathering in" (re-bracketing) process. Re-tuning
        is required at each reduction of scan range and bandwidth combination,
        and care must be exercised not to move the "coarse tuning" control
        after the stabilizer circuit is a actuated Drift effects can be
        reduced by employing faster sweep rates and wider scan ranges
        as is seen in a comparison between the middle and lower left
        hand photos in Figure 9-3. When the writing speed is increased
        from 10 sec/ div to 0.5 sec/div (20 times as fast) the display
        error decreases by a factor of 20. The $\pm$ 30 Hz sidebands which
        were displayed at $\pm$ 28 Hz at 10 sec/division are then traced at
        $\pm$ 29.9 Hz with the 0.5 sec/division because of the drift error
        reduction to 2/20 Hz.

A further increase in writing speed at this frequency scan width and resolution bandwidth would present an uncalibrated display and therefore limits any further improvement by this method.. It is important to recognize these effects in the instrumentation so that the error is not attributed to the facility emission. The drift can be minimized by allowing adequate warm-up time, holding constant ambient temperature (opening and closing windows, cycling the heater or air conditioner, etc. aggravate the effect), and maintaining constant input voltage to the analyzer.

9.3.5   <u>Bessel Function nulls as a function of Modulation Index in VOR 9960 FM sidebands.</u> The amplitude distribution of the various FM sidebands (multiples of the 30 Hz baseband in the VOR case) on the 9960 Hz subcarrier are a function of the modulation index (m). The modulation index, $m = $ deviation/baseband which is nominally 480/30 Hz $= 16$ for the VOR. The deviation in the rate at which frequency is generated results from a corresponding variation in the gap between the teeth of the tone wheel presented to the magnetic pickup furnishing the output. The 332 teeth in this tone wheel are rotating at 30 rps to produce an average frequency output of (332 x 30) 9960 Hz. The deviation (16 x 30) about this 9960 Hz center frequency is $\pm$ 480 Hz. This duration produces a bandwidth (2 x 480) of 960 Hz between 9480 and 10440 Hz. The Bessel function curves in Figure 9-8a were produced from Polynominal Approximations in section 9.4 of the National Bureau of Standards "Handbook of Mathematical Functions, 1964, edited by M. Abramowitz and I.A. Stegun. These were programmed on the Wang Calculator for sideband orders through 17 and modulation indices through 20. Three printouts separate the various traces to facilitate analytical efforts.

The 9960 Hz subcarrier in Figure 9-8b was obtained in linear rather than logarithmic mode to more easily see the relationship to the curve amplitudes of Figure 9-8a. The center line labeled J_0 in the photo corresponds to the trace labeled "Carrier (J_0)" on the graph above. All the bessel lines appear positive in the photo after detection; however, the relative amplitudes correspond to positive and negative deflections in the graph above for a modulation index equal to 16. The sideband lines are numbered to left and right of center. The lower amplitude sidebands on the graph agree with pronounced nulls in the 9-8b presentation for J_1, J_3, J_5, J_8, J_{11}, J_{12}; whereas, J_2, J_4, J_6, J_7, J_9, J_{10}, J_{13}, J_{14}, J_{15} are quite high on both the photo and graph. The J_0, J_7, and J_{16} are about the same amplitude. The amplitude beyond the J_{16} line falls off steadily so that for practical purposes the 6 dB bandwidth (see upper right display in Figure 9-9 for logarithmic presentation) is contained within 2 x 480 Hz deviation $=$ 960 Hz. This is seen to occupy about 4.8 divisions of the display at a scan rate of 200 Hz/division. The high amplitude grouping of J_{13}, J_{14}, and J_{15} produces the large spikes
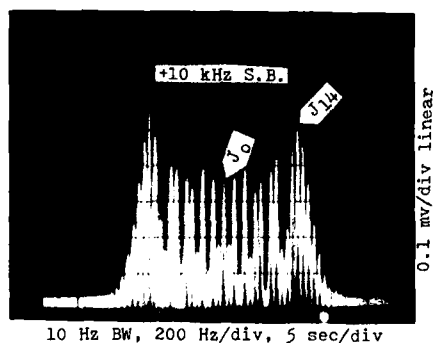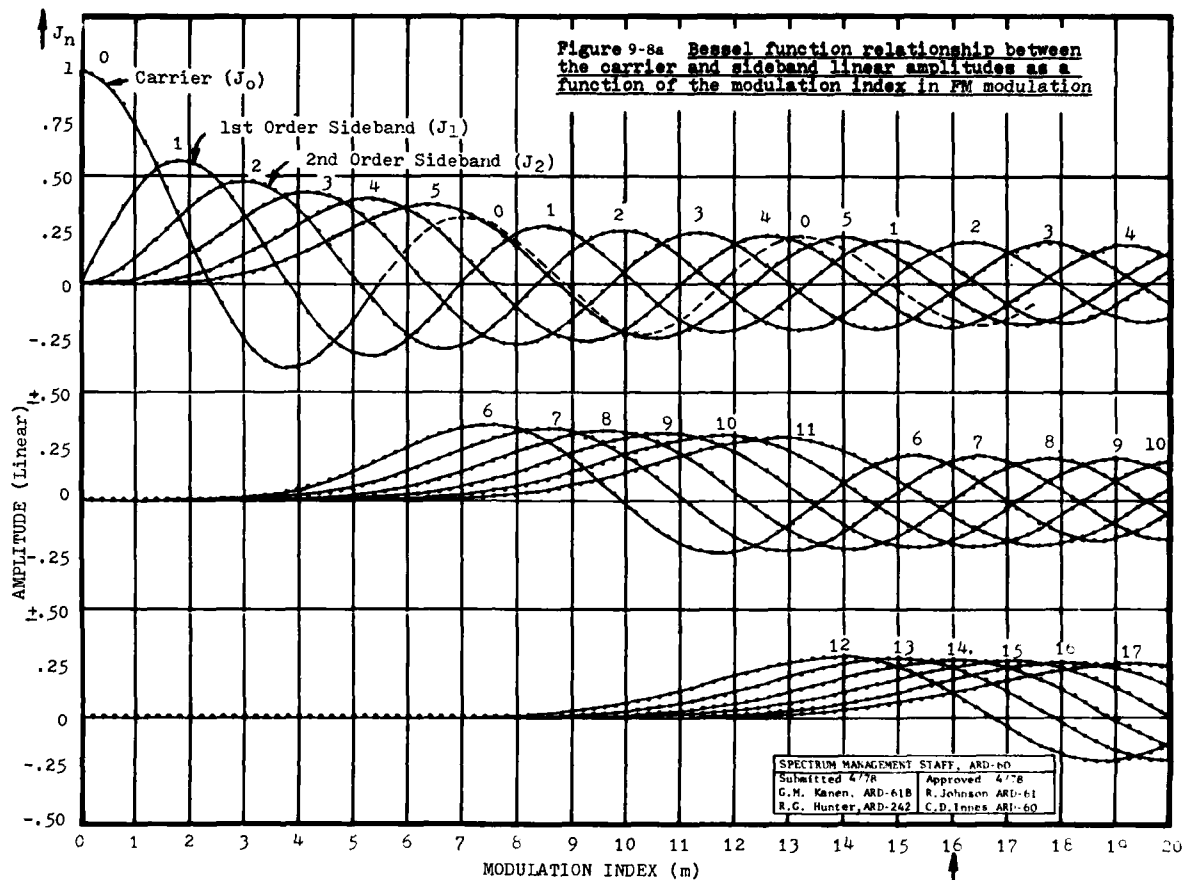
Figure 9-8a **Bessel function relationship between the carrier and sideband linear amplitudes as a function of the modulation index in FM modulation**

Carrier (J$_0$)

1st Order Sideband (J$_1$)

2nd Order Sideband (J$_2$)

AMPLITUDE (Linear)

MODULATION INDEX (m)

SPECTRUM MANAGEMENT STAFF, ARD-60	
Submitted 4/78	Approved 4/78
G.H. Kanen, ARD-61B	R. Johnson ARD-61
R.C. Hunter, ARD-242	C.D. Innes ARD-60

+10 kHz S.B.

J$_{14}$

J$_0$

0.1 mv/div linear

10 Hz BW, 200 Hz/div, 5 sec/div

Figure 9-8b <u>Linear vertical display of the FM modulation on the VOR 9960 Hz subcarrier.</u>

Negative excursions of the J$_n$ curves above appear as positive lines after detection in the 9960 Hz FM spectra at left. Note the extremely deep null at J$_8$ correlation with the bessel number 8 sideorder (0 amplitude) above. The J$_{1,3,5,8,11}$ nulls are most useful in the establishment of m - 16; however, the J$_{14}$ maximum is also seen to be in good agreement. The bandwidth between $\pm$ J$_{17}$ lines ($\frac{1}{2}$ amplitude of J$_{14}$, 6 dB drop) is about 960 Hz...or twice the maximum deviation (2 m x 30 Hz = 2 x 480 Hz).

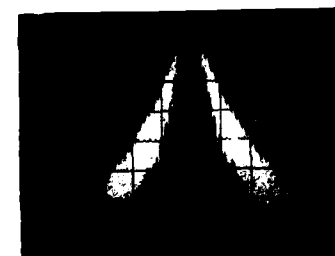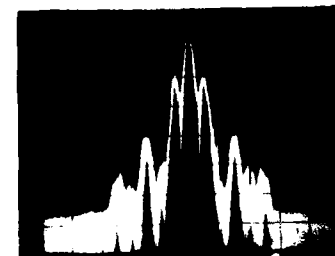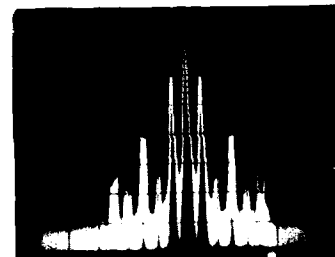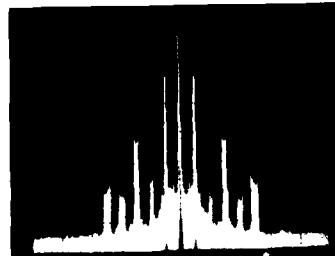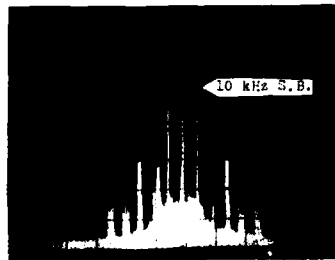on the outer edges of the 9960 Hz component and its harmonics
when the analyzer bandwidth is adequate to merge two or more lines
simultaneously within the bandpass. These effects are discussed
in sections 9.3.6 and 9.3.7 in connection with Figures 9-9 and
9-12, respectively.

9.3.6   <u>Spectrum FM component amplitudes on a conventional VOR as a
         function of emission and analyzer bandwidths.</u> The left-hand
         series of displays in Figure 9-9 indicate how the absolute and
         relative amplitudes of the signal components vary as a function
         of both the emission width and the analyzer bandpass used. The
         10, 20, 30, 40, and 50 kHz components $\pm$ from the carrier are
         1,2,3,4, and 5 kHz wide, respectively. The carrier is narrow
         band* and therefore does not vary in amplitude as the analyzer
         band pass is widened. The 10 kHz subcarrier amplitude display
         is seen to grow with analyzer bandpass widening as more FM 30 Hz
         sideband lines furnish energy to the trace deflection (right hand
         series in Figure 9-9). The individual lines spaced at 30 Hz
         intervals can be distinguished with the analyzer 10 Hz BW.
         As the bandwidth is widened to 30 Hz no longer can individual
         lines be distinguished. The amplitude of the outer peaks is
         seen to jump about 5.5 dB as two FM subcarrier lines are now
         contained in the bandpass simultaneously.

         The J_{13}, J_{14}, J_{15} lines are like individual sine wave generators
         with outputs of the form $E \sin (n)\omega t$ where $= 2\pi f$ and $f = 30$ Hz.
         The three sine waves then become $E_{13} \sin 13 \omega t$, $E_{14} \sin 14 \omega t$, and
         $E_{15} \sin 15 \omega t$, and will be reasonably in phase (Figure 9-10c) from
         time to time while within the sweeping analyzer bandpass. The
         amplitudes from Figure 9-8b lower peak are $E_{13} = .48$, $E_{14} = .55$
         and $E_{15} = .47$. Assume that J_{13} and J_{14} amplitudes are preserved
         in the nose of the bandpass, and that J_{15} is negligible because
         of excessive attenuation on the bandpass skirt. The amplitude
         jump as the analyzer is switched from 10 Hz BW (seeing J_{14}) to
         30 Hz BW (seeing J_{13} and J_{14} added) is then:

$$E_{30-10} \text{ (dB)} = 20 \log E_{30}/E_{10} = 20 \log (.55 + .48)/.55$$

$$= 5.45 \text{ dB}$$

         *Exception is per section 9.3.1 when the analyzer bandwidth is
          narrowed to below 30 Hz. The carrier and 30 Hz sideband then
          look like broadband signal to the analyzer and the carrier
          amplitude drops 2.28 dB as only one signal at a time drives
          the amplifier.

100 Hz Bandwidth, 20 kHz/div..

300 Hz Bandwidth, 20 kHz/div., 2 sec/div.

1 kHz Bandwidth, 20 kHz/div., 5 sec/div.

3 kHz Bandwidth, 20 kHz/div., 5 sec/div.

10 kHz Bandwidth, 20 kHz/div., 0.2 sec/div

Figure 9-9 Spectrum component amplitudes in a conventional VOR as a function of spectrum analyzer bandwidth. All displays were made with the same bi-conical antenna orientation at counterpoise height from a range of 100 yards. The vertical scales are all 10 dB/division. The top line reference level for all displays is -20 dBm (analyzer input attenuator is 20 dB so that a full scale reading is actually -40 dBm at the mixer to ensure linearity). An additional 10 dB is inserted at the Master Panel in the antenna line. In the overall VOR spectrum series on the left the 10, 20, 30, 40 and 50 kHz components $\pm$ from the center narrow-band carrier are 1, 2, 3, 4 and 5 kHz wide, respectively. It is observed that as the analyzer bandwidth approaches the emission bandwidth of the particular spectrum component of interest, a further increase in display amplitude is negligible with additional increase in analyzer bandwidth. For example, the 1 kHz wide upper 10 kHz sideband increase in amplitude as the analyzer is switched from 100 to 300 Hz and to 1 kHz has essentially stopped with the 1 kHz B.W. so that no noticeable change is seen when the instrument is widened to 3 kHz B.W.

The upper 10 kHz S.B. from the series on the left has been expanded in the series on the right to describe in more detail the mechanism involved in the amplitude growth with increasing analyzer bandwidth. At 10 Hz B.W. the individual FM Bessel frequency lines spaced at 30 Hz intervals can be distinguished. Note the low amplitudes of the $J_{1,3,5,8,11}$ lines and the high amplitude groupings of the $J_{13,14,15}$ lines about the midpoint which is characteristic of a modulation index = 16. In the 30 Hz BW display two lines are furnishing power to the response at any instant so the amplitude approaches $10 \log k(e_1^2 + e_2^2)^{\frac{1}{2}}$ with some allowance to analyzer response curve and produces an amplitude increase in the order of 6 dB. The 100 Hz B.W. display sees 3 lines to produce an amplitude in the order of $10 \log k(e_1^2 + e_2^2 + e_3^2)^{\frac{1}{2}}$ resulting in another increase of about 6 dB. Very little further increase results from changing the B.W. to 300 Hz because several low amplitude components are involved (also true of 1 kHz)

Shadowed trails in the 100 and 300 Hz BW displays result as the higher amplitude groupings evident in the 30 Hz BW display are encountered on the higher attenuation regions of the sweeping analyzer filter. The intensity increases as more lines fill the filter "nose" and then decreases as the analyzer sweeps past the midpoint to mirror the effect. The flat top evident in the 300 Hz and 1 kHz BW displays is the shape of the analyzer response curve seeing the average power of up to 34 lines simultaneously.

Voice identification emissions appear in the upper left display on the R.H. edge of the -20 kHz harmonic.

In the 300 Hz B.W. display on left it was possible to avoid voice emissions appearing every 30 seconds by increasing the sweep rate to 2 sec/div and still remain in amplitude calibration... (6 div x 2 sec/div = 12 seconds). During intervals when voice was present it was quite audible when passing through $\pm$ 20 kHz regions. In the 3 kHz BW configuration voice could be readily heard when the analyzer was sweeping through $\pm$ 40 kHz regions.

Note that the narrowband carrier in the left hand displays does not change amplitude as the analyzer bandwidth is increased except for a small amount in the bottom exposure where all components are contained within the bandpass.
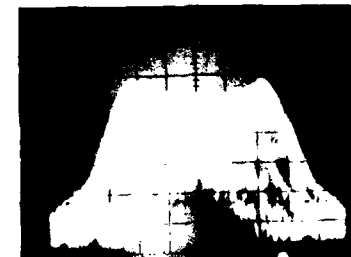
The 10 kHz B.W. encompasses all the components so the display approaches the shape of the analyzer bandpass characteristic. The envelope ripple is due to the passage of antenna pattern lobe at 30 Hz rate (6 peaks in 0.2 sec.).
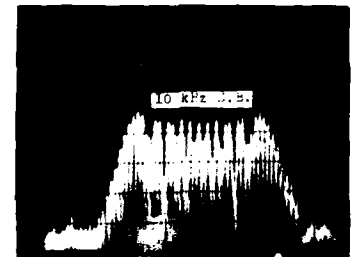
10 Hz Bandwidth, 200 Hz/div., 5 sec/div
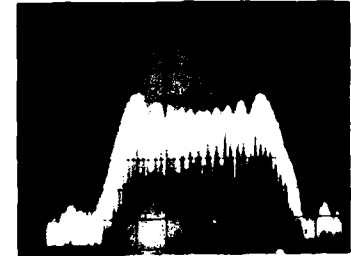
30 Hz Bandwidth, 200 Hz/div., 5 sec/div

100 Hz Bandwidth, 200 Hz/div., 5 sec/div

300 Hz Bandwidth, 200 Hz/div., 5 sec/div
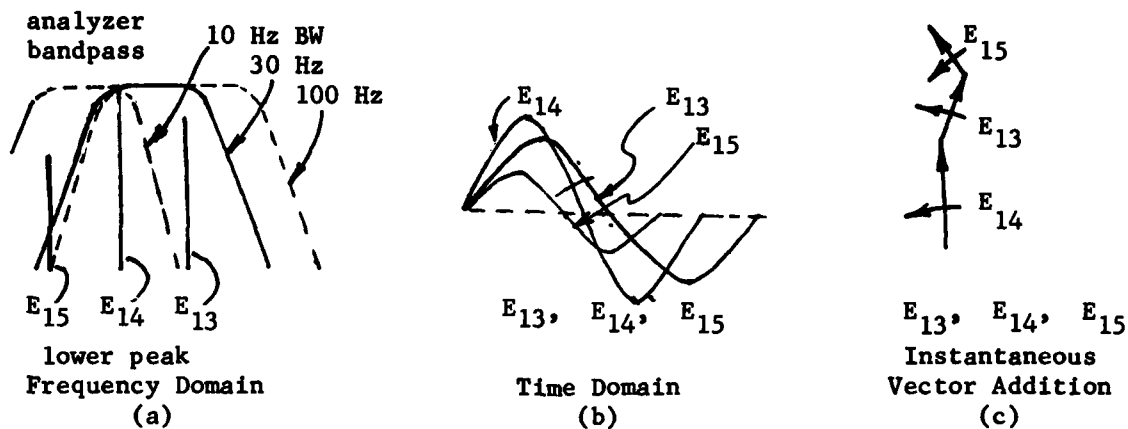

1 kHz Bandwidth, 200 Hz/div., 5 sec/div

analyzer bandpass — 10 Hz BW / 30 Hz / 100 Hz

E_{15} E_{14} E_{13}

lower peak
Frequency Domain
(a)

E_{14} E_{13} E_{15}

E_{13}, E_{14}, E_{15}

Time Domain
(b)

E_{15} E_{13} E_{14}

E_{13}, E_{14}, E_{15}

Instantaneous
Vector Addition
(c)

Figure 9-10 FM J_{13}, J_{14}, J_{15} sideband component instantaneous addition in the analyzer bandpass at the outer peaks of the 9960 emission envelope.

Note the variation in amplitude of the 11 peaks making up the Figure 9-9 right-hand 30 Hz BW display. This dip towards the center occurs because while the extreme peaks contain several J_n components, the next two pairs on either side only contain two of significant amplitude and the five center ones only contain one. The amplitude increase of the center region is relatively slight (2 dB) as the analyzer bandpass is widened from 10 to 30 Hz.

The vertical width of the trace results as the various sine wave vectors are in different states of cancellation and addition to produce the instantaneous deflection voltage over this range of amplitudes from moment to moment.

As the bandwidth is increased to 100 Hz these individual narrower line grouping peaks can no longer be separated and merge to form a valley between the two end peaks. The amplitude of the end peaks has increased another 6 dB as more lines appear simultaneously in the bandpass although the valley between the humps is maintained because the 100 Hz BW sees a line pattern with frequent nulls for about 600 Hz of sweep.

The peaks appear to have moved outward (apart) as the widened bandpass skirts furnish energy to maintain the peak amplitude farther off center frequency. These energy concentrations are lumped as evident in the 30 Hz BW display and produce the bright "trails" in the shadowed regions below the envelope in the 100, 300, and 1000 Hz BW displays as they are encountered by the lower regions of the bandpass. The narrowest analyzer bandwidth (10 Hz in this case) should be used to determine actual signal bandwidth.

The 300 Hz BW display has filled in the valley and widened
the apparent emission bandwidth to the extent that the outer
ends of the envelope are largely the shape of the analyzer
bandpass rather than presenting the signal format. This effect
is aggravated further as the bandpass is widened to 1 and 3 kHz.
Finally, all the carrier, subcarrier and harmonics are lost in
the 10 kHz lower-left display. This is predominantly the
analyzer bandpass envelope to the extent that only the 30 Hz
envelope ripple gives a hint that this is a VOR response as
the antenna pattern rotates past at 30 rps. The ripple is detected
by adjusting the sweep time rate to 0.2 sec/division since
the effect is more time than spectrum derived.

It is observed that the peaks on either end of the 10 kHz FM
display and its harmonics stop increasing significantly when
the analyzer encompasses the higher amplitude line grouping
beyond the J_{11} null; however, the center valley continues to
build up to the peak level until the analyzer bandwidth approaches
about one-third of the signal bandwidth. For this reason, the
50 kHz harmonic is believed to have essentially reached full
amplitude in the 3 kHz BW display although it is absorbed in
the 10 kHz BW display before establishing this. A plot of how
the FM component amplitudes increase as a function of analyzer
and signal bandwidths is contained in Figure 9-11. These curves
have been developed from a combination of measurement data, Fourier
analysis, and generous portions of draftsman's prerogative;
however, they do support the operating observations stated earlier
in this paragraph and are useful for establishing measurement
procedures.   For   some empirically experienced reason
most of the display amplitude has been achieved when the analyzer
BW approaches 1/3 of the FM emission bandwidth 2(30 + 480) =
960 Hz or 300 Hz (nearest BW setting on the instrument used).
However, 1 kHz may be the best compromise choice to describe the
overall carrier, sidebands and harmonics.

Inspection of Figure 9-12 shows 30 Hz line spacing preserved
in the higher ordered "harmonics." The number of these lines
present in a particular component is proportional to the order
of the harmonic. For example, the 30 kHz harmonic contains 3
times the number of 30 Hz spaced lines as contained in the 10 kHz
sideband or 32 and 96, respectively. The lobe structure of the odd
30 and 50 kHz harmonics is well defined, whereas, the 20 and 40 Hz
even harmonics contain much more distortion or noise.

The number of lobes on the 30 Hz BW pattern of the 10 kHz sub-
carrier in Figure 9-9 is multiplied by the harmonic number to
produce the number contained in the various harmonics in Figure 9-12
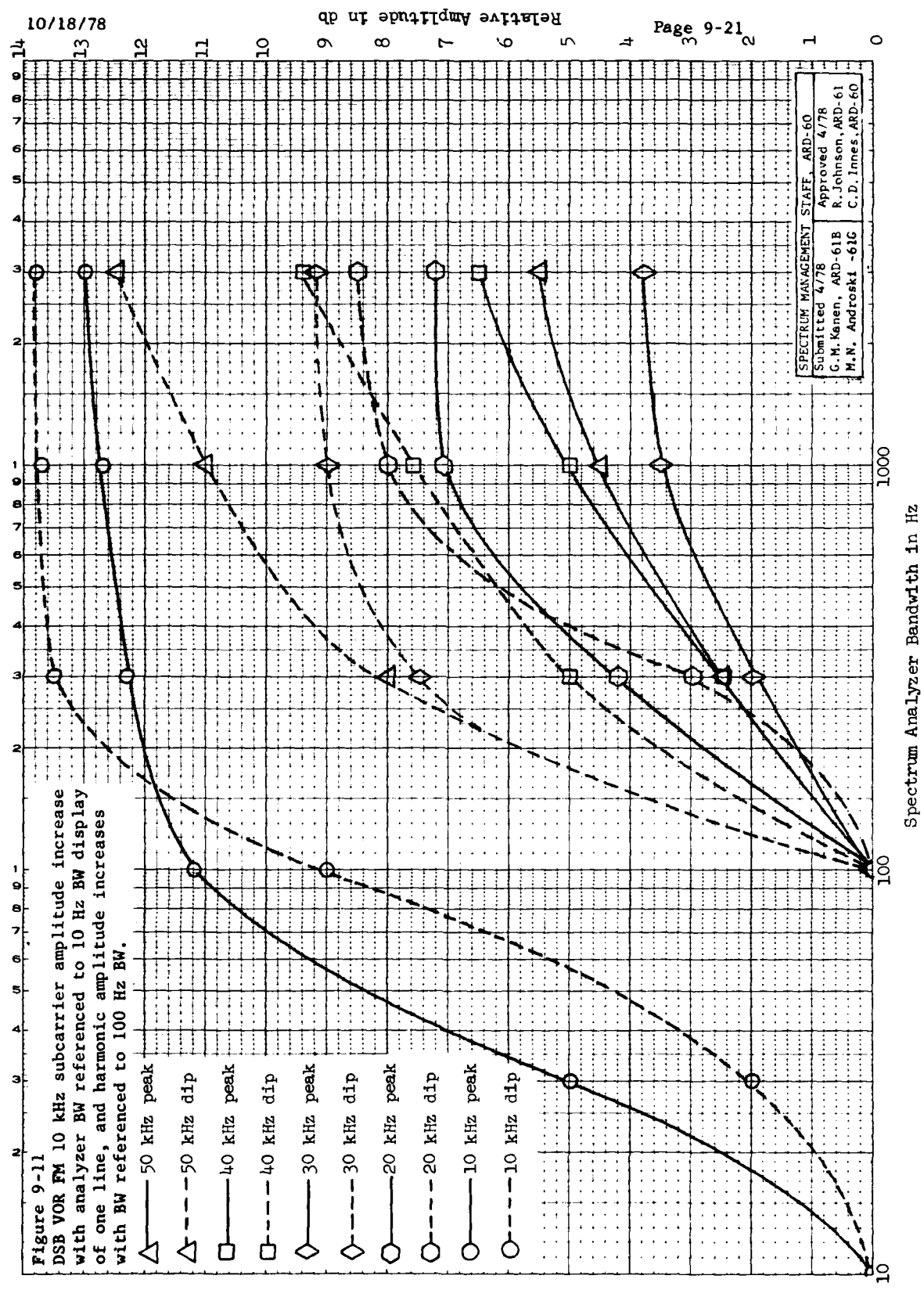...i.e. ...the -30 kHz display has 3 x 11 = 33 lobes. The

Figure 9-11
DSB VOR FM 10 kHz subcarrier amplitude increase
with analyzer BW referenced to 10 Hz BW display
of one line, and harmonic amplitude increases
with BW referenced to 100 Hz BW.

————— 50 kHz peak
- - - - 50 kHz dip
————— 40 kHz peak
- - - - 40 kHz dip
————— 30 kHz peak
- - - - 30 kHz dip
————— 20 kHz peak
- - - - 20 kHz dip
————— 10 kHz peak
- - - - 10 kHz dip

Spectrum Analyzer Bandwith in Hz

SPECTRUM MANAGEMENT STAFF, ARD-60	
Submitted 4/78	Approved 4/78
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M.N. Androski -61G	C.D.Innes, ARD-60

10 Hz BW, 200 Hz/div.

10 Hz BW, 200 Hz/div.

10 Hz BW, 10 sec/div.

1 kHz/div, 10 sec/div

10 Hz BW, 200 Hz/div., 6 sec/div.

10 Hz BW, 200 Hz/div, 10 sec/div

10 Hz BW, 10 sec/div

10 Hz BW, 10 sec/div

10 Hz BW, 200 Hz/div, 10 sec/div

10 sec/div.

Audio in -20 and +40 kHz regions

20 kHz/div, 10 sec/div

Voice in ± 17 kHz regions

1 kHz/div, 10 sec/div

10 Hz BW, 200 kHz/div, 10 sec/div

10 Hz BW, 10 sec/div

10 Hz BW, 400 Hz/div, 10 sec/div

1 kHz/div, 10 sec/div

1 Hz/div.

observation that the left hand peak (low frequency end) in both
the ± harmonics is of greater magnitude than the right hand end
is useful in determining the mechanism by which they are generated.

9.3.7   Voice and 1020 Hz tone identification emissions in the 20, 30,
          40, 50, etc. kHz harmonics on a conventional VOR.
          Voice and tone modulations occuring as the spectrum analyzer
          is sweeping in the vicinity of the harmonic frequencies are
          detected in both the display and audio outputs (See Figure 9-12)
          Either tone or voice amplitude modulations are initiated about
          every 10 seconds and have altered the - 20 and + 40 kHz harmonic
          displays markedly in the center photo (i.e...the +40 kHz appears
          greater than 5 kHz wide, the -20 kHz too wide, etc.).

          Figure 9-13 expands the harmonics to show the voice and 1020 Hz
          tone identification intermixes. The sweep rate was adjusted
          appropriately to display the audio transmissions (for example,
          the 3 second duration tone ident would be displayed in 3 divisions
          out of 10 by selecting a 1 sec/div sweep rate). This audio display
          was positioned by actuating the single-sweep mode a proper interval
          before the modulations start (for example, in the upper photo of
          the -40 kHz harmonic series the sweep was started 3.3 seconds prior
          to the first character of the tone ident) in order to center the
          tone display. The tone amplitude is relatively constant over the
          frequency range displayed indicating that this is more a "time
          domain" (amplitude as a function of time) presentation (see section
          9.3.8 for a further discussion on discerning or separating time
          and frequency effects). The even and odd numbered harmonics appear
          to the left and right sides of Figure 9-13, respectively to show
          the amplitude addition and subtraction impact of the audio on the
          spectrum envelope. In general the audio adds to the even numbered
          harmonics and subtracts from the odd numbered ones. In the -40
          kHz series the identification tone AML (._   __ ._..) appears
          to be inserted in the bowl-shaped harmonic spectrum which is a
          "frequency domain" (amplitude as a function of frequency) display.

          In the 300 Hz BW display of the -40 kHz harmonic the darkened end
          sections appearing like the wide open ends of a pipe elbow are
          essentially the bandpass response of the 300 Hz filter which
          darkens as one half sweeps beyond the emission envelope limit.
          This is seen to hold true as the bandpass was widened (3:1) to
          1 kHz. The broadband "white" noise presents the bright "grass"
          threshold along the base. The darkened areas represent regions
          where no energy level exists for long enough to print at the intensity
          used. The uppermost bright areas represent the signal envelope where
          the rate of change of amplitude of the composite signal peaks is
          changing slowly enough to illuminate the screen. The darkened "V"
          at the center of the 1 kHz BW displays occurs as equal amounts
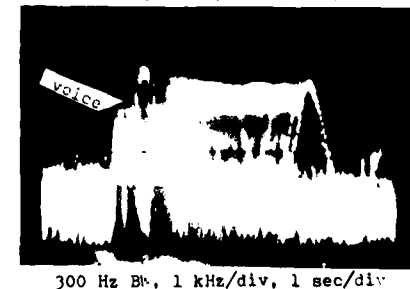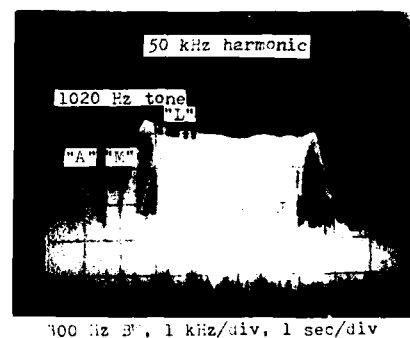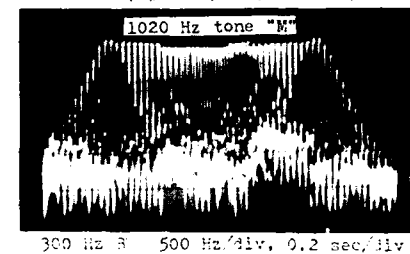   of high energy are encountered in both bandpass "skirts" to maintain
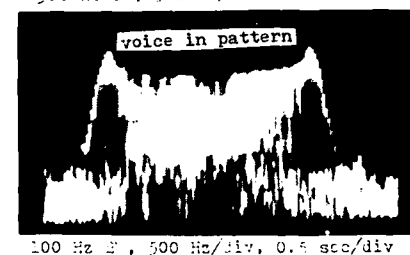
+20 kHz harmonic

1020 Hz tone "M" "L"   Voice

10 log/div

... Hz B', 500 Hz/div, 1 sec/div

+30 kHz harmonic

1020 Hz tone ident "A" "M" "L"

300 Hz B', 500 Hz/div, 1 sec/div

-40 kHz harmonic

1020 Hz tone ident "A" "M" "L"

300 Hz BW, 500 Hz/div, 1 sec/div

voice in pattern

100 Hz B', 500 Hz/div, 0.5 sec/div

1 kHz BW, 500 Hz/div, 1 sec/div

1020 Hz tone "M"

300 Hz B, 500 Hz/div, 0.2 sec/div

kHz BW,   Hz/div, 0.5 sec/div

50 kHz harmonic

1020 Hz tone "L"

"A" "M"

300 Hz B', 1 kHz/div, 1 sec/div

+60 kHz harmonic

1020 Hz tone "A" "M" "L"

300 Hz BW, 1 kHz/div, 1 sec/div

voice

300 Hz BW, 1 kHz/div, 1 sec/div

Figure 9-13 Voice and 1020 Hz tone in the 20, 30, 40, and 50 kHz harmonics of a conventional VOR emission spectrum. The interference is manifested in an amplitude increase in the even (20, 40, 60 kHz) harmonics; whereas a decrease in amplitude occurs on the odd harmonics.

the illumination threshold at its highest point. The composite
(addition & subtraction) effects of the azimuth pattern and
unmodulated tone carrier create the bright stripes in the darkened
area between tone characters (dots and dashes); whereas, during tone
modulation the bright upper limits of the envelope appear to be
largely a function of the tone amplitude. The open bowl effect
in the upper (300 Hz BW) -40 kHz display is created as the more
slowly varying regions of the antenna pattern (max/min = 5 dB...
...see Figure 9-9, 10 kHz BW) passing 30 times per division com-
bine with the composite energy contained within the bandpass at
the particular sweep location, instant by instant, to record two
distinct levels in the upper envelope. This combined time and
frequency domain effect coupled with antenna pattern modulation
is also very evident in the +60 kHz display. The rather noisy
+20 kHz display indicates that the 1020 Hz tone amplitude appears
relatively constant whether superimposed on the noise threshold
or on the +20 kHz envelope. The difference in tone amplitude
in the +20 kHz display and the voice which commences 4 seconds
later is in the order of 5 or 6 dB. This harmonic mix tone/voice
difference is not consistant with the 13.5 dB amplitude variation
expected from the 6 and 30% modulations (see Figure 9-7) in the
basic processes before the spurious generation.

It is evident in the right hand series of odd harmonic displays
in Figure 9-13 that the phasing of the tone and voice carrier
subtracts from the harmonic carriers in a manner to create a
negative modulation effect on the spectrum envelope. In the upper
50 kHz harmonic photo the "A" and "M" appear positive with respect
to the noise but the "L" appears to be a negative excursion as it
is imposed on the harmonic envelope. The apparent 30 Hz lines are
a time rather than frequency function as discussed in section
9.3.8 following.

9.3.8   Distinguishing between time and frequency domain effects in
         spectrum displays. A variation of bandwidth, dispersion, and
         sweep rate controls is used to distinguish whether lines in the
         display are due to frequency or time varying characteristic in
         the emissions being measured. For example in Figure 9-8 the
         bandwidth has been narrowed to 10 Hz to distinguish between FM
         spectrum lines 30 Hz apart. The number of lines appearing per
         division using a dispersion of 200 Hz/division is then 200/30=6.66.
         Similarly, in Figure 9 -12, a 10 Hz bandwidth has been used to
         examine a portion of the +30 kHz harmonic and the lines making
         up this emission are seen to occupy 30/50 of a division at 50 Hz/div
         dispersion. -A further refinement for counting results from
         counting 10 peaks (10 x 30 = 300) in 6 divisions (6 x 50/div = 300).
         These lines are characteristic of a particular frequency mod-
         ulation process so that the display amplitude is primarily a
         function of frequency. The ±30 Hz AM variable signal spectrum
         lines evident in Figures 9-3, 9-6 result from the 30 cps

rotation of the antenna variable pattern; however, the Figure
9-3 envelope ripple (15 peaks per division per 0.5 sec = 30 Hz)
from this same antenna pattern source is a time domain function
superimposed on the frequency domain presentation (lower left
display). While this space modulated sideband pattern is developed
by feeding carrier to the modulation bridge and goniometer the
resulting effect in space (as seen by examining the amplitude
ripple on the lower left display of Figure 9-3) is as if a
negligible amount of carrier is contained in the rotating pat-
tern. This conclusion is based on the antenna pattern ripple
which is prevalent on the bandpass envelope in the vicinities
of 30 Hz and its' 60, 90, etc. harmonics, but decreases in ampli-
tude to approach zero (barely perceptible threshold) at the
carrier frequency. The ripple amplitude is difficult to assess
as it is contained on the bandpass slope; however, if the band-
pass is broadened to 10 kHz to contain most of the higher energy
lines of the emission as in Figure 9-9 (lower left) the peak-
to-peak difference in antenna composite pattern gain is seen to
be in the order of 5 or 6 dB (ref. section 9.3.1). The amplitude
range of brilliance shading in the right-hand displays of Figure
9-9 are more a function of the vector addition range of values
over the interval (see Figure 9-10) than due to fluctuation of
antenna pattern level, because the 9960 Hz originates from the
constant amplitude omni-directional reference portion of the
emission (see Figure 9-4).

The relationship between the time interval (t) for a periodic
waveform to complete a cycle and the frequency (f) of occurence
is expressed by the relationship $f = 1/t$. In Figure 9-13 the
lower photo in the +30 kHz harmonic series contains 6 lines per
division or per 0.2 second which relates to (lines/div x 1/t/div =
6 x 1/.2) 30 Hz. To distinguish whether this is primarily a 30 Hz
time or frequency product the frequency selective control and
display aspects are investigated. The 300 Hz bandwidth used is
not capable of separating spectrum lines spaced at 30 Hz intervals.
It is further noted that at a dispersion of 500 Hz/div the
six lines/division would be separated by 500/6 = 83.3 Hz which does
not seem to be a meaningful or likely product of the VOR mechanisms.
Changing the sweep rate further confirms the time dependant aspect
as in the middle photo where 15 lines per division appear over an
interval of 0.5 seconds indicating a 30 Hz characteristic. The
number of spectrum lines (frequency dependant) per division will
not vary with change of sweep rate (they are not a time function).
Increasing the sweep time to 1 sec/div doubles the lines (30 lines/
div...merge to appear continuous). The number of lines is proport-
ional to the sweep rate if they are time dependant. Confusion can
arrive when the analyzer controls are set to give conflicting results
if the time and frequency analysis answers are in close agreement.
If the operator expects to find 30 Hz spectrum lines (middle photo...
500 Hz/div) and miscounts the 15 time dependant lines (one line
error) to get 500/30 = 16.6 lines/division he may draw the wrong
conclusion. The likelihood of doing this increases with the dif-

ficulty of counting the lines as in the lower photo of the
-40 kHz series where the lines are run together with the wider
bandpass (1 kHz/100 Hz); however, it is realized that the 1 kHz
bandwidth could not distinguish between spectrum lines separated
by 30 Hz. These lines can be detected on top of the code char-
acters. The prime contributor to time display effects in this
discussion is the variation in signal resulting from the 30 cps
rotation of the VOR antenna pattern. A brief inspection of the
Figure 9-4 composite pattern sketch shows that the rate of
change of signal amplitude is much less in the maximum and min-
imum gain regions (top and bottom as pictured) than the quadrature
regions (sides). This characteristic intensifies the spectrum
waveform during passage of the slowly changing level portions
(when the intensity control is adjusted to distinguish these
levels). This time varying amplitude in conjunction with freq-
uency line variations enhances or creates unusual displays such
as the bowl-shaped (2 level upper envelope) effect in the -40
kHz upper and the +60 kHz photos. Judicious manipulation of the
analyzer controls as illustrated in the above examples can pro-
duce much added information about the emission provided that
both operational and analytical procedures are employed to avoid
false conclusions.

9.4   DOPPLER VOR (DVOR). The DVOR employs 50 Alford Loop antennas
           around the perimeter of a 44 foot diameter circle (see Fig. 9-14)
           to reduce reflection errors in adverse terrain environments.
           The AM and FM sideband roles are interchanged from the conventional
           VOR configuration so that the FM sideband contains the variable
           signal. The aircraft receiver FM detector "capture effect" then
           minimizes the impact of weaker reflected FM variable signal
           components containing course errors.

           A distributor feeds the sideband antennas consecutively around
           the 44' circle 30 times per second. This cyclical variation in
           distance about the mean range between the center of the facility
           array and the aircraft produces a nominal $\pm$ 480 Hz Doppler
           shift with similar characteristics in space about the f_c + 9960
           Hz carrier as are produced by the tone wheel FM modulation on
           the $\pm$ 9960 subcarrier sidebands in the conventional VOR. The
           carrier antenna in the center of the array is simultaneously
           radiating an RF signal from the higher powered carrier transmitter
           at a frequency, f_c. The heterodyning of these two signals in
           the receiver produces an effective 9960 Hz subcarrier deviated
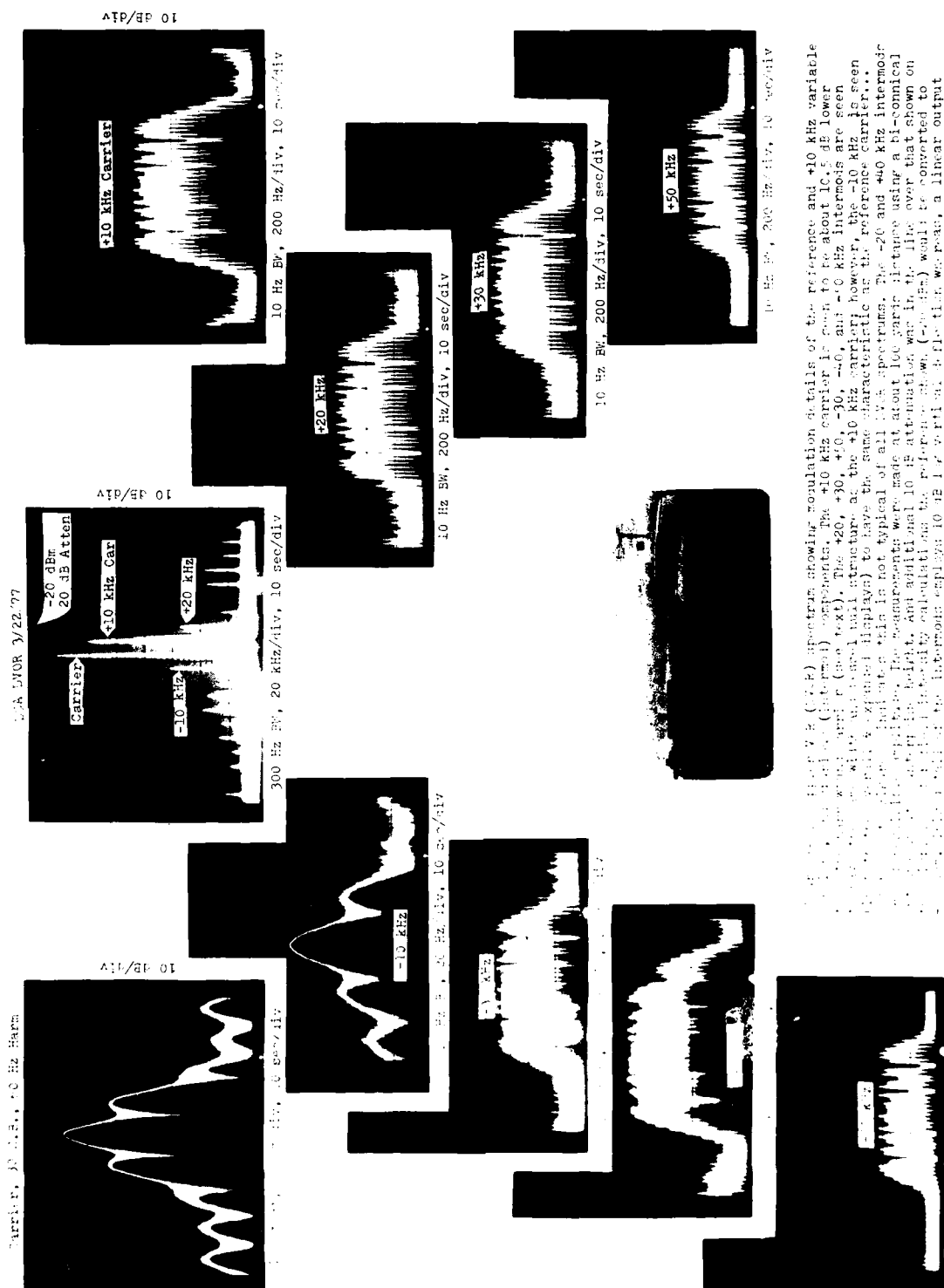 $\pm$ 480 Hz to provide a post-detection 30 Hz variable signal.

Figure 9-14. DVOR showing 44' diameter circle of 50 Alford
Loop antennas above a 150' diameter counterpoise. The carrier
loop is housed in the conical enclosure which is topped off with
the DME antenna. The monitor antenna is in the right foreground.

9.4.1   DVOR spectrums. A typical DVOR spectrum as received in space
          is shown in Figure 9-15. Note in the center display that the
          transmitter driving the higher frequency carrier is adjusted
          to produce about 10.46 dB less power in space than the main
          carrier transmitter; however, a greater difference is seen on
          the spectrum analyzer (approaching 12.7 dB as covered in section
          9.3.1 and Fig. 9-7) at bandwidths greater than 30 Hz.

          Inspection of the upper left display indicates a carrier to
          30 Hz sideband fixed-phase signal difference in excess of 16.48 dB
          because of the analyzer display problem just referenced above
          (see Fig. 9-7). Note the similarity to conventional VOR Fig. 9-3
          upper left display.

          The 10 kHz spaced side products are seen to be the same width
          in a DVOR emission instead of getting progressively wider as they

10 dB/div

+10 kHz Carrier

+10 kHz

10 Hz BW, 200 Hz/div, 10 sec/div

+20 kHz

10 Hz BW, 200 Hz/div, 10 sec/div

+30 kHz

10 Hz BW, 200 Hz/div, 10 sec/div

+50 kHz

10 Hz BW, 200 Hz/div, 10 sec/div

10 dB/div

SA IVOR 3/22/77

−20 dBm
20 dB Atten

Carrier

+10 kHz Car

−10 kHz

+20 kHz

300 Hz BW, 20 kHz/div, 10 sec/div

10 dB/div

−10 kHz

10 dB/div

Figure ... (...) spectrum showing modulation details of the reference and +10 kHz variable ... The +10 kHz carrier is seen to be about 16.5 dB lower ... (a + xt). The +20, +30, +40, −30, −40, and −50 kHz intermods are seen ... structure as the +10 kHz carrier; however, the −10 kHz is seen ... (lower) displays) to have the same characteristic as the reference carrier... this is not typical of all SSB spectrums. The −20 and +40 kHz intermods ... measurements were made at about 100 parts picture using a bi-conical ... And additional 10 dB attenuation was in the line over that shown on ... calculated the reference shown, (a − 165) would be converted to ... intermods employ 10 dB of variable 6 dB tilt was read, a linear output ... visible in figure.

depart from the carrier as characteristic of the VOR.
This lends insight as to how they are produced and suggests
that they might be more properly referred to as intermods than
harmonics.   These may be generated by the 9960 Hz reference
voltage in the automatic frequency control (AFC) equipment.
The normal D.C. voltage output to maintain the sideband trans-
mitter exactly 9960 above the carrier picks up some undesirable
RF and the resulting heterodyne of 9960 Hz "frequency" modulates
the sideband transmitter. A number of "modulation products"
spaced at 10 kHz intervals on either side of the carrier result
which are single-tone or CW in nature before being space
modulated by the distributor/antenna system. In space the
modulation products appear with similar FM characteristics
to those of the desired sideband carrier, namely $\pm$ 480 Hz.

In the conventional VOR a 9960 Hz tone is generated with $\pm$ 480 Hz
FM modulation which is then amplified and plate modulated on the
carrier transmitter. Non-linearities in the amplifiers and
transmitter RF power amplifier cause true harmonics to be generated
before being applied to the antenna system. These are symmetrically
distributed about the carrier although improper transmitter
neutralization can introduce some non-symmetry. Since these
are true harmonics, the deviation on them increases with the
harmonic number so that the second harmonic located 20 kHz
above the carrier is twice as wide as the desired 10 kHz
sideband (2x 2 x 480 = 1920 Hz, instead of 980 Hz BW), the
third is deviated three times as much (3 x 480 = 1440, or
2 x 1440 = 2880 Hz BW), etc.

Since the output voltage of a slope detector is proportional
to the amount of frequency deviation in the signal, the third
harmonic of a conventional VOR could produce three times as
much error as the third modulation product of a DVOR in the
aircraft receiver.

Inspection of the +10 kHz carrier and the +20, +30, $\pm$50, -40,
and -50 kHz intermods in Figure 9-15 shows the same bessel
null structure and bandwidth.

In Figure 9-15 the -20 and +40 kHz intermods are of negligible
amplitude. Variations in intermod structure at different DVOR
facilities is discussed in section 9.4.3.

9.4.2   DVOR spectrum-component amplitudes as a function of spectrum
             analyzer BW. Note in Figure 9-16 that the main (narrowband)
             carrier does not vary in amplitude as the analyzer BW is
             changed   until the 10 kHz BW is reached (both xmtr powers
             are then driving the I.F. simultaneously). The relative ampli-
             tudes of the various intermods is preserved as the analyzer
             bandwidth exceeds 1 kHz, whereas the wider emissions in the
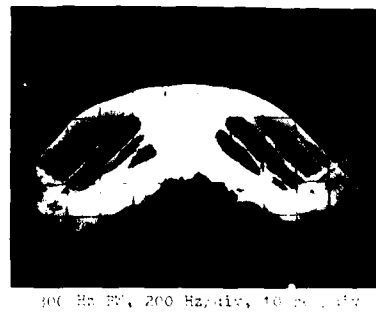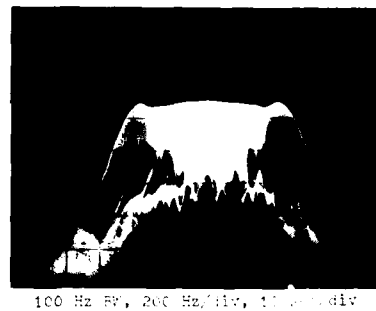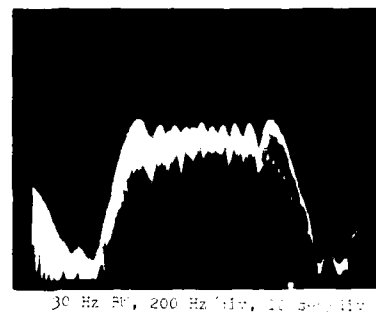   conventional higher ordered harmonics continue to grow.
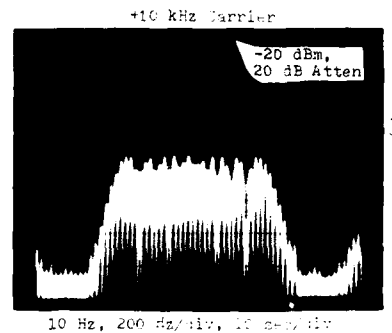
DCA DVOR

100 Hz BW, 20 kHz/div, 10 sec/div

+10 kHz Carrier

-20 dBm, 20 dB Atten

10 Hz, 200 Hz/div, 10 sec/div

300 Hz BW, 20 kHz/div, 10 sec/div

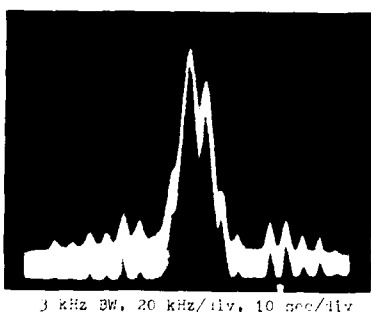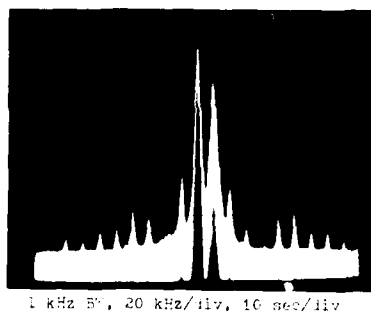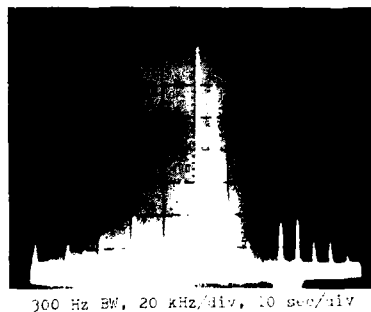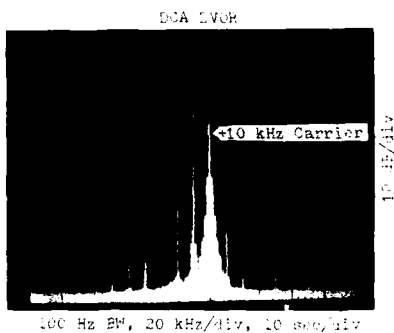30 Hz BW, 200 Hz/div, 10 sec/div
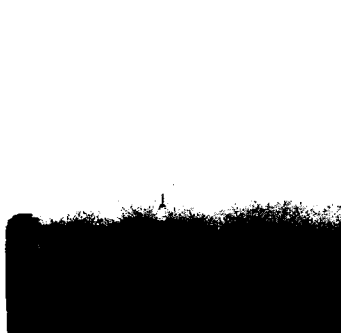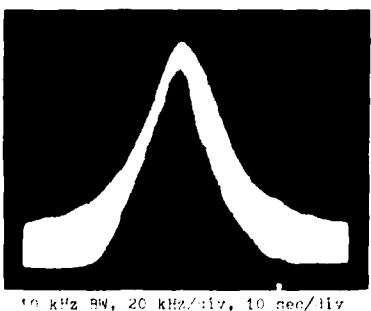
Figure 9-16 Doppler VOR (DVOR) spectrum component amplitudes as a function of spectrum analyzer bandwidth. The narrowband reference carrier in the left series does not change amplitude with analyzer bandwidth until the 10 kHz BW display where the +10 kHz carrier is present within the bandpass simultaneously. (see text for increase calculation). The -10 kHz intermod is predominantly narrowband (see Figure 9-18 for detail); however it's amplitude does grow at a lesser rate with bandwidth due to other distortion. This will vary with characteristics of this -10 kHz intermod at different DVOR facilities. The amplitude jump of about 5 dB in switching from 100 Hz BW to 300 is more pronounced than in the conventional VOR because the Bessel nulls are not as emphasized (see right hand series for the + 10 kHz carrier)... although the same $\pm J_{3,6,8,11}$ lines are attenuated. Note the swayback effect in Figure for the 100 Hz BW detail on the + 10 kHz carrier compared to the humpback (rise at mid-envelope) at center-right. In the left-hand series the + 10 kHz amplitude increases until the 1 kHz BW encompasses essentially all the significant lines (upper-right...about 34) and then shows relatively no increase as the BW is widened to 3 kHz...this is seen to be true for the various intermod components also since they are the same width (which differs from the conventional VOR case in Figure 9-9).

The shortwave trail structure evident in the 100 and 300 Hz BW displays to the right are formed as the line groupings (about 11) shown in the 30 Hz BW display are encountered by the higher attenuation regions of the analyzer bandpass "skirt" as it sweeps through the signal from left to right. In the left-hand series as the bandpass is widened to exceed the width of the emission the envelope becomes largely that of the analyzer filter being used. In the upper left the series of shoulders on the + 10 kHz carrier are formed by 1600 Hz (30 Hz commutator rps x 50 antennas) switching transients.

The intermods are seen to increase in amplitude in an oscillating manner (like sin x/x) ...see Figure 9-17 for a comparison of spectra from a number of different DVOR sites.

1 kHz BW, 20 kHz/div, 10 sec/div

100 Hz BW, 200 Hz/div, 10 sec/div

3 kHz BW, 20 kHz/div, 10 sec/div

300 Hz BW, 200 Hz/div, 10 sec/div

10 kHz BW, 20 kHz/div, 10 sec/div

1 kHz BW, 200 Hz/div, 10 sec/div

The amplitude jump of about 5 dB in switching from 100 to
300 Hz BW is more pronounced than in the conventional VOR
because the Bessel nulls are not as pronounced. This also
accounts for the center hump (Fig. 9-16, right-center) in
the DVOR using 100 Hz bandwidth as compared with the sway-
back in Figure 9-9 (right-center).

9.4.3   Differences in DVOR modulation product amplitude roll-offs
          at various facilities. The fall-off in amplitude of the mod-
          ulation products at 10 kHz intervals varies from an orderly
          exponential type of decay as a function of frequency depart-
          ure from the carriers at some facilities to an oscillating
          sinx/x type of roll-off about the sideband carrier at others.
          This is illustrated in Figure 9-17. The decay is rapid and
          non-oscillating in the top two displays. In the middle left
          a few intermods are distinct but decay rapidly with frequency.
          In the lower left and right displays the intermods are evi-
          dent for more than 100 kHz departure from the 10 kHz side-
          band carrier and exhibit a sinx/x type of roll-off super-
          imposed on the exponential decay envelope.

          Changing transmitters on the Figure 9-17 lower-right facility
          had little effect on the radiated spectrum as shown in
          Figure 9-18; however, the output from facility "A" upper-
          right was altered noticeably by changing transmitters as
          indicated in Figure 9-19.

          At several facilities the intermod 10 kHz below the main
          carrier was found to be decidedly narrowband (CW spike)
          compared to the intermods.

9.4.4   Switching transients. A switching transient is generated as
          the distributor couples by the gap feeding the 50 antennas
          30 times per second producing a composite 1500 Hz pulse
          spectra. This is shown for the SEA facility in Figure 9-20.

          In Figure 9-21 there is little difference in the radiated
          spectra when transmitters are switched with respect to the
          switching transients disposed about the C + 9960 carrier.

          In Figure 9-22 the SMO DVOR switching transients produce
          spectra about the 9960 sideband carrier which are quite
          different from those at the facilities documented in Figures
          9-20 and 9-21 all of which are extracted from the site
          displays in Figure 9-17. Note that the more "squared-off"
          switching displays for the SEA and DCA (Figure 9-23) correlate
          with the extended sinx/x roll-off of intermods in Figure 9-17.
          The SMO, ANN, and "A" switching displays are less squared
          (more dips and transcedental type of envelope) and relate to
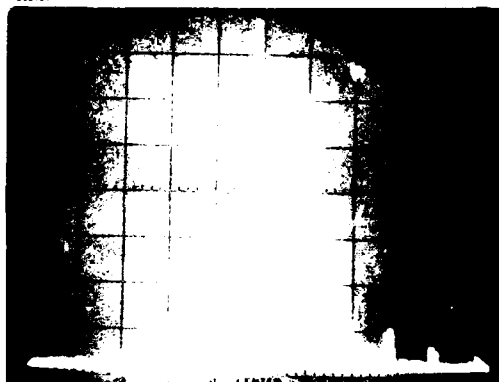   the rapid decay (more exponential) of intermods in Figure 9-17.

SMO
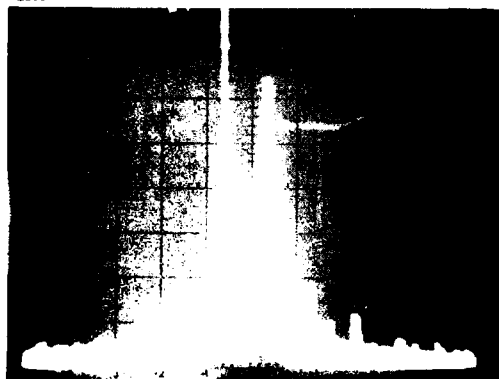
100 Hz BW, 10 kHz/Div
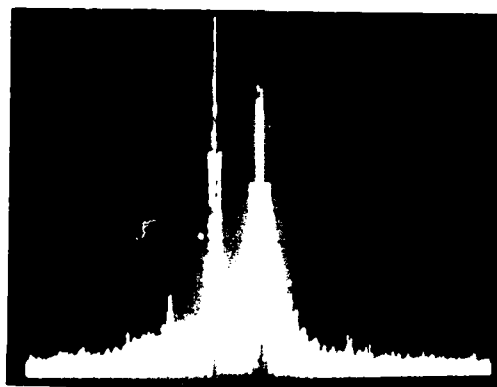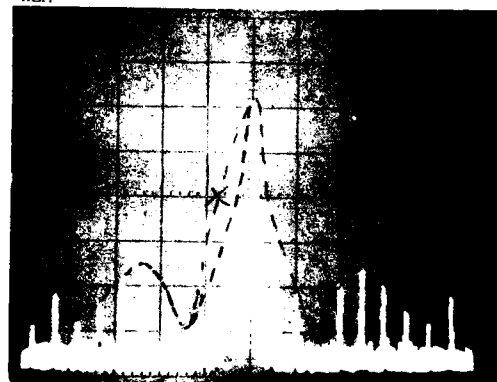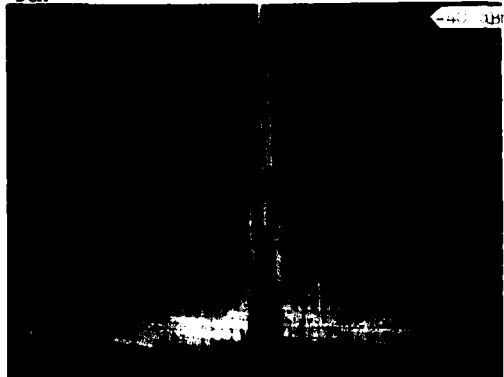
100 Hz BW, 10 kHz/Div

ANN

SEA

100 Hz BW, 10 kHz/Div

300 Hz BW, 20 kHz/Div

DCA

10 dB log

Figure 9-17 DVOR carrier and sideband carrier with related intermod products distributed at 10 kHz intervals. Note the correlation between the SMO and "A", rapid decay of intermod envelope and the hollowed out, 1500 Hz switching peak spectra in Figures 9-21 and 9-22. The sinx/x decay roll-off of the SEA and DCA facilities correlates with the more squared off (higher centered) switching peak spectra in Figures 9-20 and 9-23.

10 kHz/Div, 300 Hz IF BW, 100 Hz
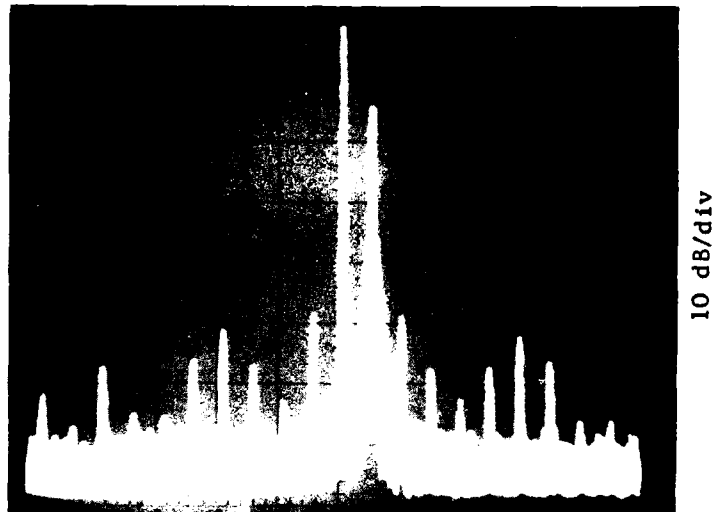
SEA No. 1 Xmtr.

300 Hz BW, 20 kHz/div

Figure 9-18 Comparison of number one and two transmitters at the
SEA facility indicates little change in the radiated emissions.

SEA No. 2 Xmtr
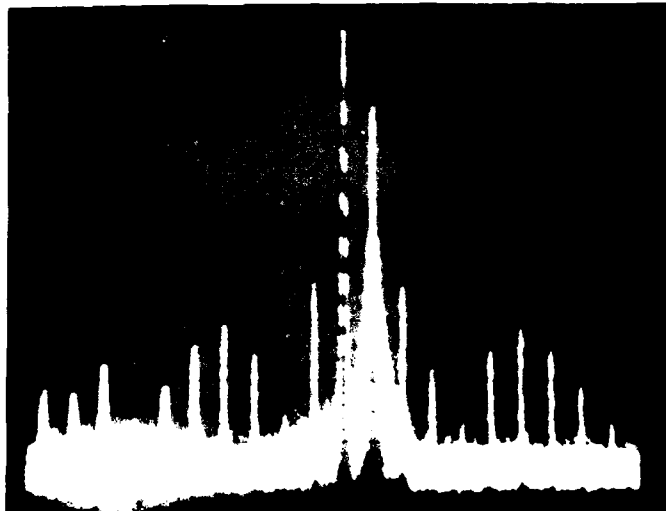
300 Hz BW, 20 kHz/div

"A" No. 1 Xmtr.
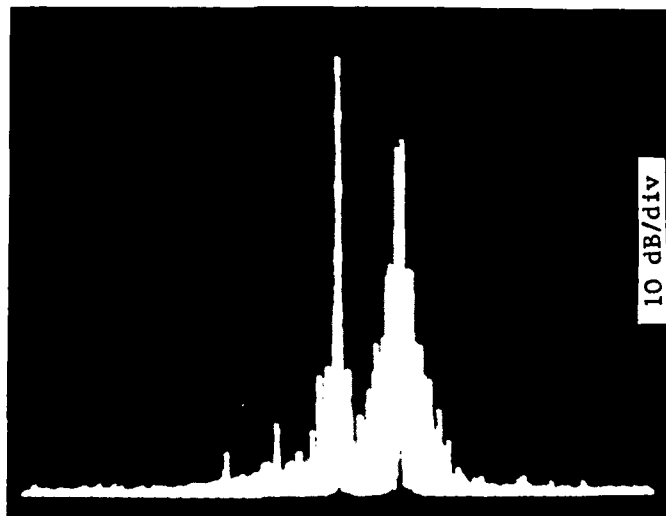
100 Hz BW, 10 kHz/div

Figure 9-19 Comparison of number one and two transmitters at
Facility "A" indicates a significant difference in intermods.
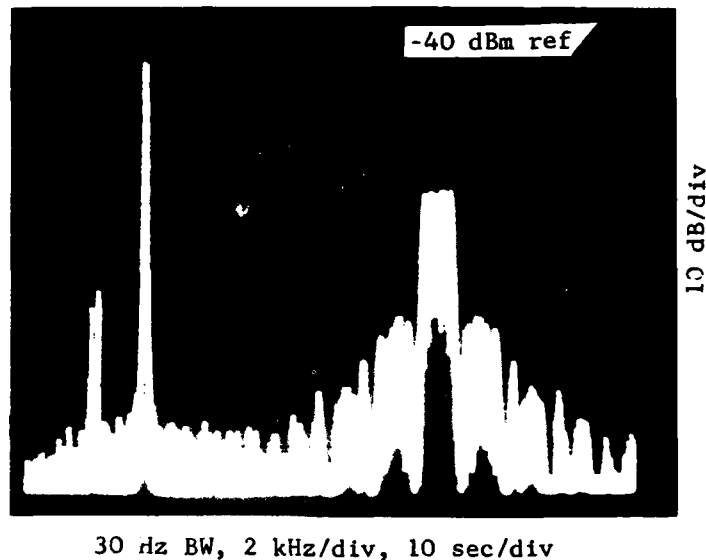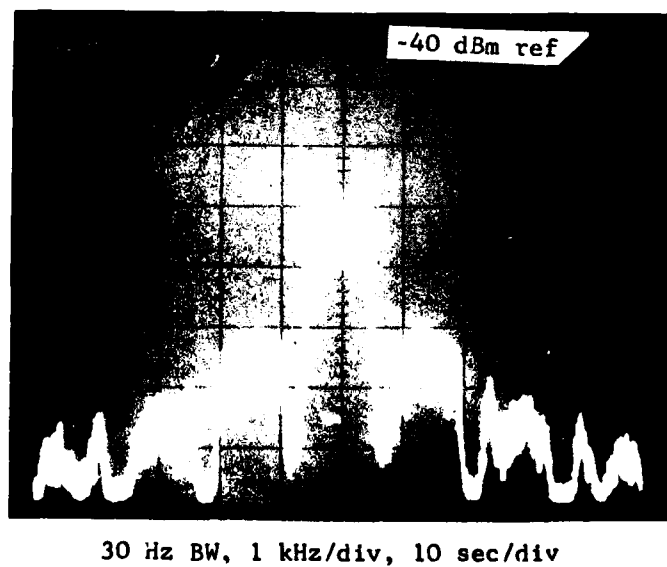
"A" No. 2 Xmtr

100 Hz BW, 10 kHz/div

30 Hz BW, 2 kHz/div, 10 sec/div

Figure 9-20 SEA 1500 Hz switching transients on the 10 kHz
variable signal carrier. The spike 2 kHz below the main
carrier is probably voice occuring as the sweep moved past
at 10 sec/div.

30 Hz BW, 1 kHz/div, 10 sec/div

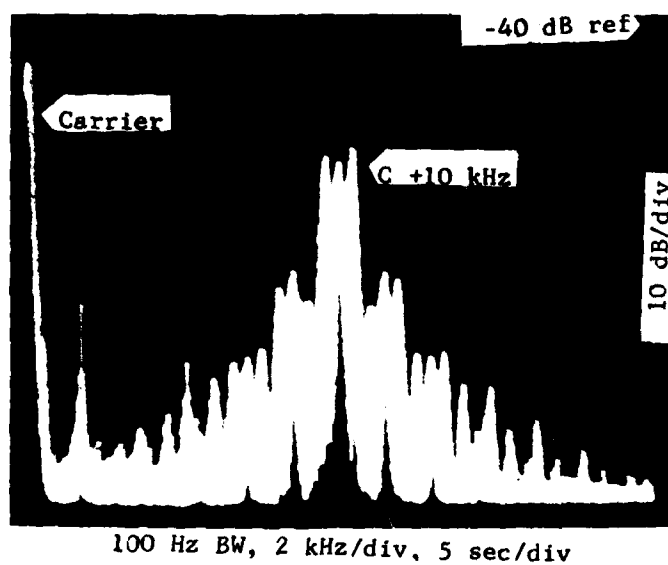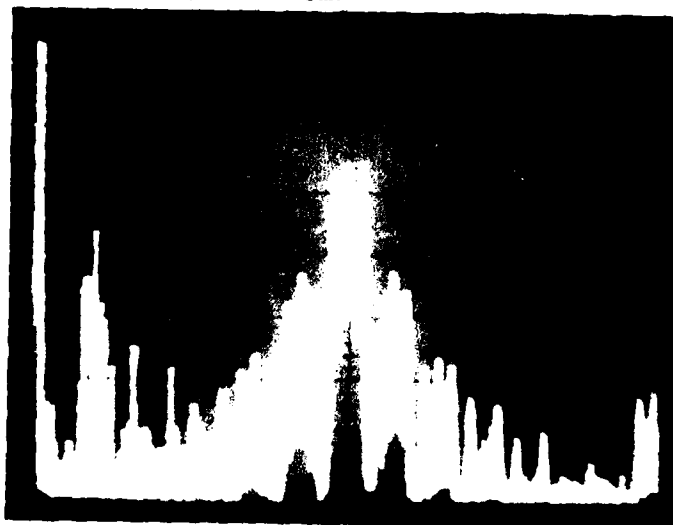"A" No. 1 transmitter

100 Hz BW, 2 kHz/div, 5 sec/div

Figure 9-21   Facility "A" 1500 Hz switching transients on the
10 kHz variable signal carrier indicate little difference
between transmitters 1 and 2. Note the triple-peak ordered
pattern compared to the flatter-noisier peak in Figure 9-20.

"A" No. 2 transmitter
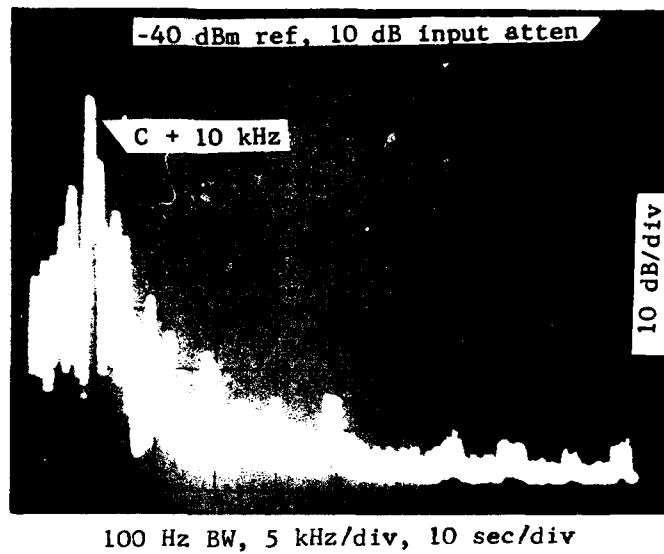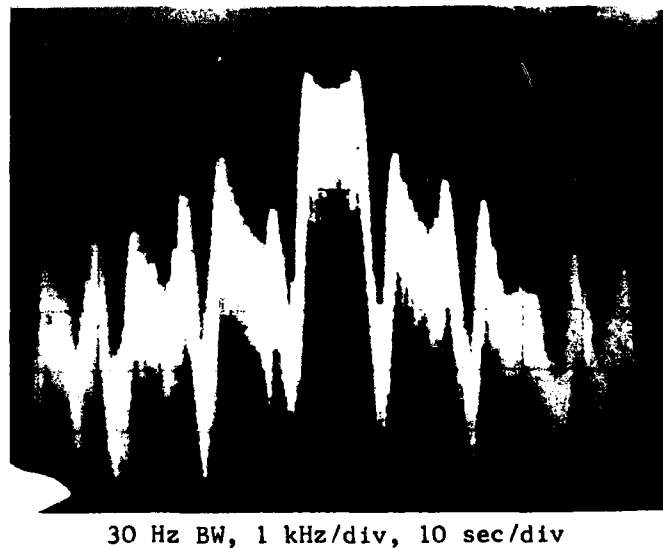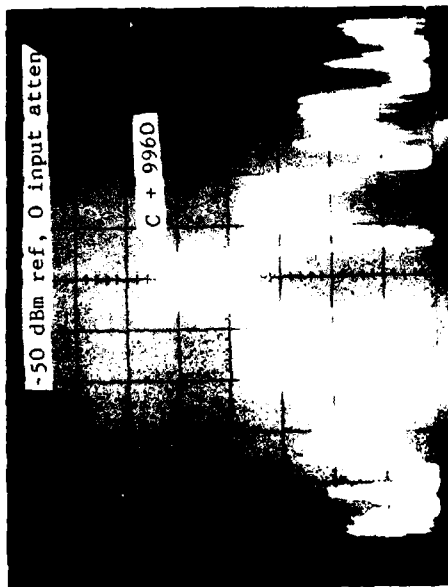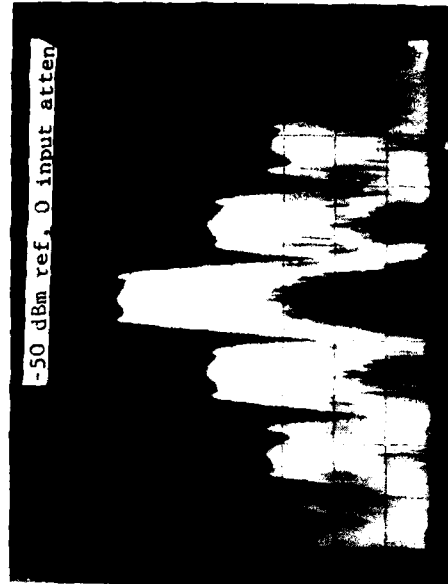
100 Hz BW, 5 kHz/div, 10 sec/div

Figure 9-22. SMO DVOR 9960 Hz variable signal carrier 1500 Hz switching transients. The low amplitude center sections of each peak in the lower display correlates with the rapid decay of higher ordered (20, 30, 40 kHz...etc.) intermods in the upper display.
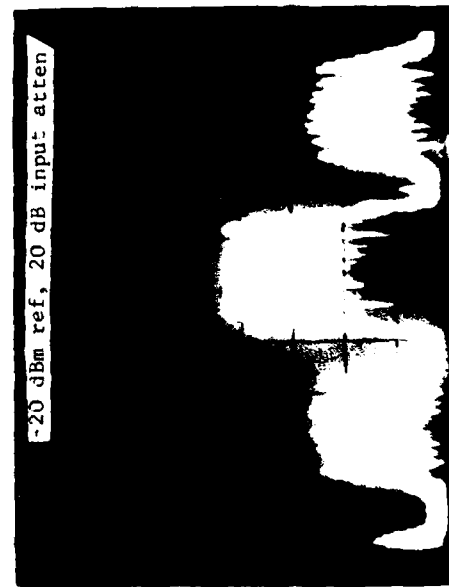

30 Hz BW, 1 kHz/div, 10 sec/div

-50 dBm ref, 0 input atten

100 Hz BW, 1 kHz/div, 10 sec/div

-50 dBm ref, 0 input atten

100 Hz BW, 500 Hz/div, 5 sec/div

-50 dBm ref, 0 input atten

C + 9960

30 Hz BW, 1 kHz/div, 10 sec/div

-20 dBm ref, 20 dB input atten
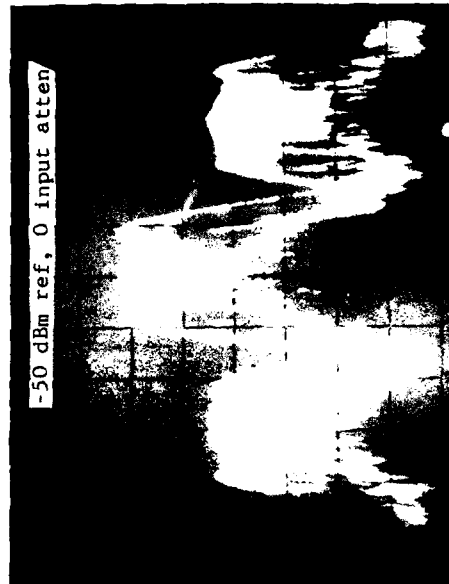
10 Hz BW, 500 Hz/div, 10 sec/div

Figure 9-23. DCA DVOR 1500 Hz switching spectra about the C + 9960 Hz carrier
Note how the high centered portion of the relatively squared peaks correlates
with the sinx/x type roll-off of higher ordered intermods in Figure 9-17.

The shape of the 1500 Hz switching spectra is a function of the distributor pole gap shape, orientation, and spacing.

9.5   <u>Spurious components in spectrum displays contributed by the measurement instrumentation.</u> In section 9.2.2 considerations affecting valid spectrum measurements included mixer input levels, etc. to avoid generation of spurious components in the displays contributed by the instrumentation system. Figure 9-24 shows multiples of a conventional VOR emission spectrum repeated on either side of the desired signal. The problem appeared instantaneously, varied levels from time to time and cleared up alternately. The problem was a defective I.F. section in the analyzer which was permanently corrected with subsequent repair of the I.F. plug-in unit. In this situation the problem was not associated with poor operating technique; however, it is important to recognize an unusual display and determine that the VOR facility itself is not the source.

9.6   <u>Optimum bandwidths for spectrum analyzer measurements of VOR and DVOR emissions.</u> Annex 10 of the International Civil Aviation Organization (ICAO) paragraph 3.3.5.7 and the U.S. National Aviation Standard for the VORTAC system section 3.4.1.4 specify harmonic levels not to be exceeded with respect to the 9960 Hz component.

In the DVOR spectrum, the 9960 Hz spaced multiple products (20, 30, 40 kHz...etc.) are deviated the same amount as the FM sideband carrier so that the display amplitudes are correct as seen with a 1 kHz bandpass analyzer.

On conventional VOR spectrums a wider analyzer bandwidth such as 3 kHz could be selected, for example, to include the 2 and 3 kHz emission widths for correct display amplitude of the 20 and 30 kHz products, respectively; however, this would cause the 10 kHz FM component amplitude to appear too large if included in the same scan because of less rejection of carrier energy in the analyzer band-pass skirts. If the bandwidth is held constant at 1 kHz during a scan of all components in a conventional VOR spectrum, correction factors must be added to the display amplitudes of the wider deviation products to convey their true composite amplitudes. The magnitude of 30 Hz signal derived from slope detection of these 9960 multiple products on the selectivity skirt of a receiver tuned to the next adjacent channel is generally dependant on the amount of deviation. The approximate correction factors to be added to the analyzer 1 kHz bandwidth displays are indicated in Figure 9-11 for one facility widths of 2, 3, 4, and 5 kHz on the 20, 30, 40, and 50 kHz harmonics or multiple products, respectively, of the conventional VOR.

Inspection of Figure 9-11 indicates that a compromise BW choice of 1 kHz is beyond the knee of the relative change curves so that amplitude errors as a function of BW would be minimized.

Figure 9-24 VOR Spectrum with spurious components in the display generated in the analyzer IF unit. Note the lower amplitude spurious repetitions of the carrier and sidebands offset ± 50 kHz from the signal. A change of 10 dB input attenuation between the 11:56 and 11:59 displays for linearity check indicates corresponding changes in the input signal (but the lower amplitude components did not change as much, thus confirming that they are internally generated). A VOR signal above about -30 dBm at the mixer may begin to exhibit non-linear behavior in low amplitude components; however it is noted that the -27 dBm signal is only -47 dBm at the mixer because of the 20 dB input attenuation setting. The 11:59, 12:05 and 12:08 display varied without adjustment of analyzer settings. The spurious components made an abrupt rearrangement heard in the audio output of the analyzer between 12:05 and 12:08 displays. Shortly afterward the display cleared up by itself. The problem seems to be associated with the stabilizer circuit. Broadening the sweep, turning off the stabilizer, retuning, narrowing the sweep, turning on the stabilizer removes the spurious but causes the frequency to jump as the stabilizer is turned. A similar unit has been used over a period of years without this type of performance. A marked departure from the expected display is cause to question the measurement performance in the general case.
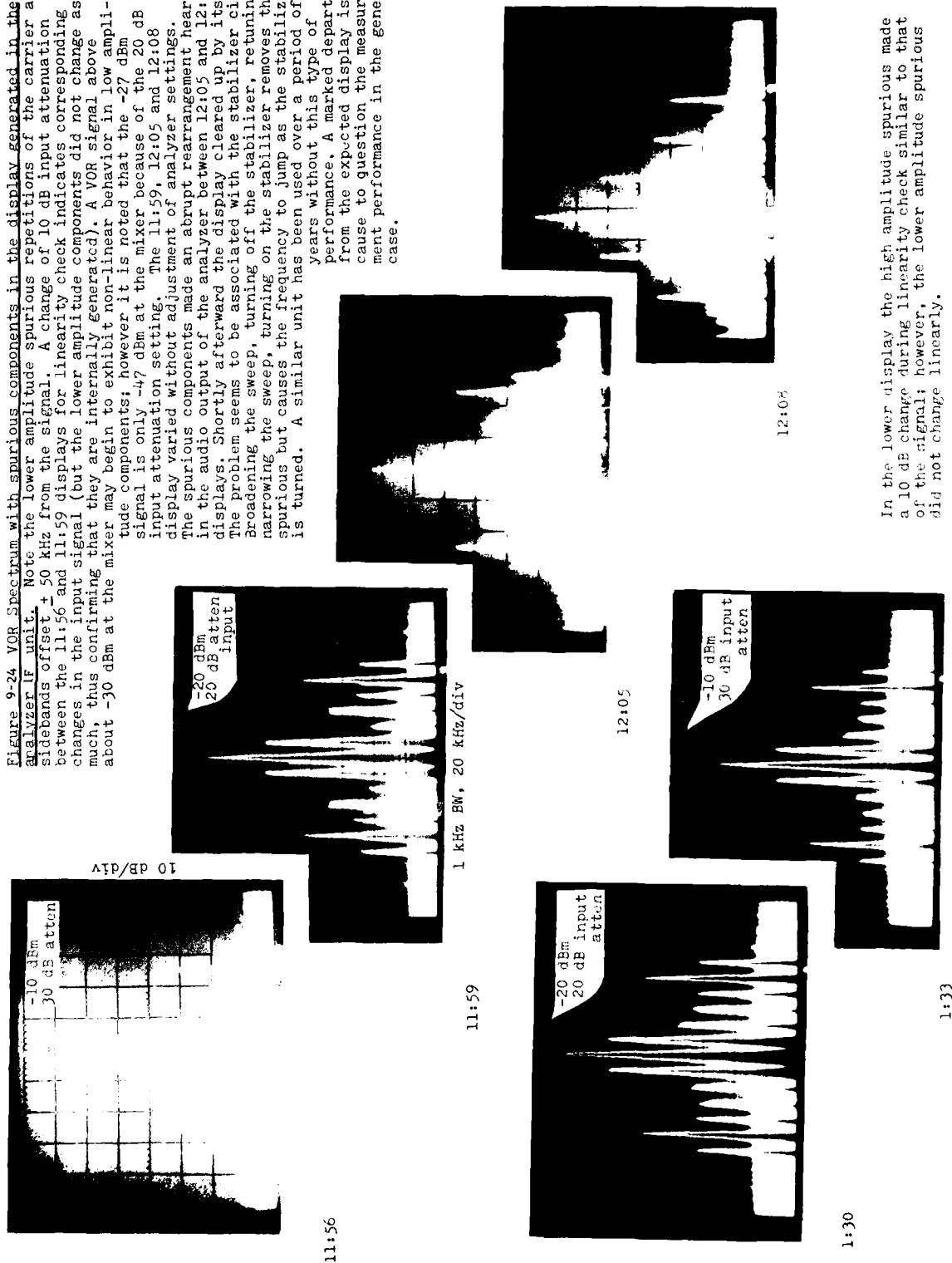
In the lower display the high amplitude spurious made a 10 dB change during linearity check similar to that of the signal; however, the lower amplitude spurious did not change linearly.

-10 dBm
30 dB atten

-20 dBm
20 dB atten
input

10 dB/div

1 kHz BW, 20 kHz/div

11:59

11:56

12:05

12:08

-10 dBm
30 dB input
atten

-20 dBm
20 dB input
atten

1:33

1:30

An alternate approach provides better signal detail but
requires an analyzer bandwidth of 10 Hz or less to resolve
the VOR 30 Hz sideband lines. The display of typical DVOR
9960 Hz FM carrier with 30 Hz detail may show 3rd, 5th, 8th,
and 11th order sideband components of relatively low ampli-
tudes which is characteristic of a modulation index equal to
16. High amplitude groupings are represented by sideband
orders 13, 14, and 15, for example, which are about one-
quarter of the unmodulated carrier amplitude as determined
by reference to bessel functions (Figure 9-8). This indicates
that these amplitudes as seen in a 10 Hz analyzer display
would produce a 1 kHz bandwidth display about 12 dB (20 log 4)
greater (in the order of 13 dB, empiricaly in Figure 9-11).
A similar procedure may be used on any of the FM components
noting that the modulation index and sideband orders will
be greater for the 20, 30, 40, etc. products in the conventional
VOR spectrum. The FM component display amplitudes do not
experience uniform increases for similar bandwidth ratio changes.
For example, a change in bandwidth from 10 (sees one sideband
primarily) to 30 Hz (sees 3 sidebands with some rejection)
results in amplitude changes as discussed in section 9.3.6
and Figure 9-11 (representative of one facility).

Analyzer bandwidth compromise for relative amplitude display
conclusions: The choice of a 1 kHz bandwidth for VOR spectrum
measurements enables the relative amplitudes of the desired
AM and FM signal components to be displayed. While some
compromise of detail is incurred, the use of narrower bandwidths
requires appreciably greater correction factors. If this BW
is not available on some analyzers inspection of Figure 9-11
indicates that greater BW choices in the order of 2 or 3 kHz
would also be satisfactory.

9.7   Importance of radiated spectrum measurements for analytical
         and adjustment purposes to assist installation, maintenance,
         and inspection of VOR, DVOR facilities. Spectrum displays
         of the VOR emission as received by the analyzer antenna
         contain valuable system performance information. These
         displays contain significant detail for analyzing the per-
         formance of various parts of the system as for example:

         1. Space modulation: Unbalance of 30 and 9960 Hz sideband
             components (Fig. 9-3 top), % modulation (section 9.3.1)...

         2. 60, 90, 120 Hz hum (Fig. 9-6) contributions to duantal,
             quadrantal, octantal...errors. . This needs some flight
             work to determine levels which are significant.

         3. FM deviation (Fig. 9-8).

4. Audio voice and tone in harmonics (Figure 9-13).

5. Harmonic and intermod levels (20, 30, 40, 50 kHz...products
Figures 9-9, 9-11 VOR: Fig 9-16 DVOR).

6. DVOR 1500 Hz switch transient spectra (Fig. 9-20, 9-21,
9-22, 9-23) importance to distributor adjustments....

7. Attenuation of modulation products (harmonics, intermods)
in exponential and sinx/x manner-(Fig. 9-3, 9-9) VOR,and
DVOR (Fig. 9-16, 9-17, 9-18, 9-19).

Once irregularities are detected in the radiated spectra addit-
ional "hard-wired" connections within the system can be made
with the analyzer to isolate problems.

A basic set of VOR radiated spectrum displays taken from
specified locations would have value in basic facility records.
Subsequent display samples could be taken remotely without
disturbing the facility. Comparison of these with the site
record set then gives insight into system performance and
thereby assists as a guide for maintenance and flight inspection
activities.

VOR REFERENCE PUBLICATIONS

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   Aviation Standard for the VORTAC System.

2. International Standards and Recommended Practices, Aero-
   nautical Telecommunications, Annex 10 to the Convention
   on International Civil Aviation (ICAO).

3. FAA Handbook 6050.5A* Frequency Management Engineering
   Principles, Geographical Separation Criteria for VOR,
   DME, TACAN, ILS, and VOR Frequency Assignments, 3/12/1969.

4. IM P 6790.4 Installation Instructions for VHF Omniranges,
   7/1/63, FAA document.

5. FAA Order, 6790.4 Maintenance of VHF Omnirange Equipment,
   28 October 1965, reprinted 10 Sep 71.

6. IM P 6790.5 Installation Instructions for Doppler VHF
   Omniranges, 1/15/64, FAA document.

7. FAA Handbook 6700.11 VOR/VORTAC SITING CRITERIA, August
   7, 1968.

* This handbook has been revised. The updated document is
  currently being reviewed. Publication of Order 6050.5B is
  expected in early 1979.